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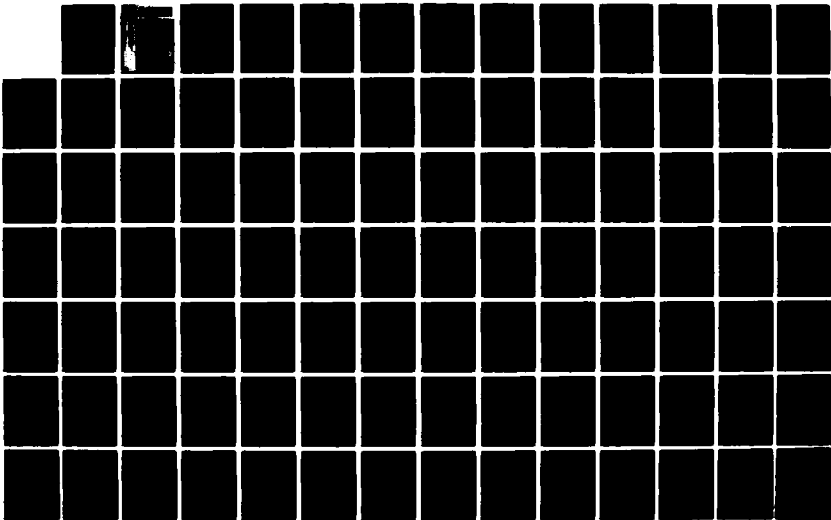

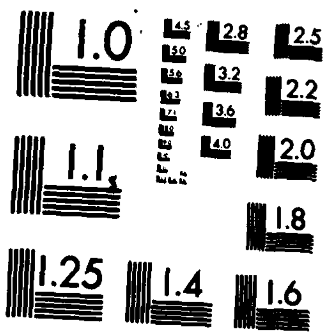
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THERMOPHYSICAL PROPERTIES OF AIRCRAFT STRUCTURAL MATERIALS IN SOLID AND MOLTEN STATES

A Comprehensive Survey of Available Data and Feasibility Study of Estimation and Measurement

Y. S. TOULOUKIAN
Director

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Assistant Director - Research

Prepared for

LASER HARDENED MATERIALS AND STRUCTURES SUBPANEL
High Energy Laser Review Group

August 1974

Prepared by

THERMOPHYSICAL AND ELECTRONIC PROPERTIES
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a comprehensive survey of available experimental data and of a feasibility study of data estimation and measurement on thermophysical properties of twenty-one selected specific and generic groups of aircraft structural materials in both solid and molten states. The capabilities of major experimental facilites in the United States have also been surveyed. Tentative estimate of research costs is given based upon the requirements for data extraction, analysis, synthesis, and generation of recommended or estimated values and for experimental determinations using

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19. KEY WORDS (Cont)

Polycarbonates---Silicone resins---Aluminum oxide---Boron nitride---Pyroceram---Silica---Silicon---Silicon carbide---Silicon nitride

20. ABSTRACT (Cont)

the existing techniques and facilities.

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FOREWORD

This report was prepared by the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC), a DoD Information Analysis Center operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana.

This report is an update and expansion of an earlier report prepared by TEPIAC and dated May 1974. It is intended to provide guidance and assessment in depth concerning the urgently needed information to the Laser Hardened Materials and Structures Subpanel of the High Energy Laser Review Group (HELRG).

This report responds to a set of requirements and specifications set forth by a tri-service group consisting of Dr. G. L. Denman (AFML), Dr. J. T. Schriempf (NRL), Mr. K. Tauer (AMMRC), and Mr. S. Valencia (AMMRC). The specific and generic groups of materials of interest was transmitted to TEPIAC on 30 July 1974 and are listed in the Introduction to this report together with the thermophysical properties and required accuracy criteria.

Because of the general lack of specific material names at this time, the study covers the information on those applicable materials in each generic group on which data are available. It must be understood that it would be prohibitive to prepare an exact assessment of both the technical and fiscal parameters on such a short notice and limited input. Hence, the discussion presented reflects only the best expert assessment in each instance and relies heavily on staff experience at times drawing heavily on unavoidable extrapolations.

It is felt that the man-hour and dollar figures reported in the summary table in the section on costs estimate reflect a fair picture of the overall situation. These figures could be used most profitably at this stage more as guidelines for planning and management purposes in phasing the program and arriving at priorities in the activation of specific projects. In preparing this study, consideration was also given to completing the initial phase of the outlined program over a 30-month period.

ABSTRACT

This report presents the results of a comprehensive survey of available experimental data and of a feasibility study of data estimation and measurement on nine thermophysical properties of twenty-one selected specific and generic groups of aircraft structural materials in both solid and molten states. The capabilities of major experimental facilities in the United States have also been surveyed. Tentative estimate of research costs is given based upon the requirements for data extraction, analysis, synthesis, and generation of recommended or estimated values and for experimental determinations using the existing techniques and facilities.

CONTENTS

I. INTRODUCTION

The purpose of this report is to present the results of a comprehensive survey of available data and feasibility study of data estimation and measurement on nine thermophysical properties of twenty-one selected specific and generic groups of materials in solid and molten states. This is in response to a set of requirements and specifications set forth by a tri-service group for providing urgently needed information to the Laser Hardened Materials and Structures Subpanel of HELRG.

The specific and generic groups of materials selected by the tri-service representatives for coverage in this comprehensive survey and feasibility study are as follows:

	Melting Point (K)	Reference No.
1. Metals		
(1) Aluminum Alloy 2024	775–911	34753
(2) Aluminum Alloy 7075	750–911	34753
(3) Titanium Alloy 6Al–4V	1803–1908	10941
(4) Hadfield manganese steel	1470–1480	Estimated by TEPIAC
2. Composites		
(1) Boron fiber aluminum metal matrix composite		
(2) Boron fiber epoxy composite	~590 (epoxy resin decomposition temperature)	43475
(3) Graphite fiber aluminum metal matrix composite		
(4) Graphite fiber epoxy composite	~590 (epoxy resin decomposition)	43475
3. Transparent Materials (visible canopies)		
(1) Acrylic resins	250–350 (softening)	90004
(2) Lucite	397 (softening)	90004
	648 (decomposition)	52896
(3) Polycarbonate plastics	415 (Lexan glass transition)	36001
	428 (Lexan softening)	40338
	500–530 (Lexan M. P.)	36001
(4) Silicone resins	473–873 (thermal degradation)	90031

	Melting Point (K)	Reference No.
4. Dome Materials		
(1) Aluminum oxide (Al_2O_3, Wesgo Al-300)	2315	90028
(2) Boron nitride (BN)	2600 ±100 (decomposition at 1 atm)	90028
	3273 (sublimation under nitrogen pressure)	26008, 45833
(3) Calcium aluminum silicate (Corning 9753)	1723-1773	28664
(4) Magnesium fluoride (MgF_2, Kodak IRTRAN 1)	1528	39947
(5) Pyroceram (Corning 9606)	1623 (softening)	25075
(6) Silica (SiO_2, fused)	1996	90028
	1950-2000	34753
(7) Silicon	1685	90027
(8) Silicon carbide (SiC, in dense bulk form and chemical vapor deposited coating form)	3260 (decomposition)	90028
(9) Silicon nitride (Si_3N_4, in dense bulk form and chemical vapor deposited coating form)	2200 (dissociation)	26008, 29054

The thermophysical properties and the accuracy requirements are as follows:

	Acceptable Uncertainty (%)	
	Normal Temperature	Vicinity of Melting Point
1. Transport Properties		
(1) Thermal conductivity	15	30
(2) Thermal diffusivity	15	30
(3) Thermal radiative emittance	10	25
(4) Thermal radiative reflectance	10	25
(5) Thermal radiative absorptance	10	25
(6) Thermal radiative transmittance	10	25
2. Thermodynamic Properties		
(1) Thermal expansion	10	10
(2) Specific heat	10	10
(3) Heat of fusion	10	10

The wavelength range of interest for thermal radiative properties is from 1 to 12 μm, in which two wavelengths of particular importance are 3.8 and 10.6 μm.

The results of the data survey and of the feasibility study of data estimation and measurement are presented in Section II. The temperature ranges (and also the wavelength ranges for the thermal radiative properties) of the available data for each property of each material are given together with the data source references. For each of the cases where data are not available, the results show whether data estimation is possible, whether measurement using existing technique and facility is possible, or whether new technique and/or facility is required for measurement. These results are given for four temperature ranges: (1) normal temperature, (2) normal temperature to 50° below the melting point, (3) 50° below the melting point to the melting point, and (4) melting point to 20° above.

In connection with the feasibility study of experimental determination, the capabilities of major experimental facilities in the United States to measure the desired properties have been surveyed. The results of this survey are reported separately.

Presented in Section IV is the tentative estimate of costs based upon the requirements for data extraction, analysis, synthesis, and estimation and for experimental determinations using the existing techniques and facilities.

The complete bibliographic citations of the references are given in Section V.

Since most of the selected materials are not well known, a concise description of the materials is given in the Appendix.

II. RESULTS OF SURVEY OF AVAILABLE EXPERIMENTAL DATA AND OF FEASIBILITY STUDY OF DATA ESTIMATION AND MEASUREMENT

Presented in this section are the results of a comprehensive survey of the available experimental data on nine thermophysical properties of twenty-one selected aircraft structural materials in solid and liquid states. The temperature ranges (and also the wavelength ranges for the thermal radiative properties) of the available data for each property of each material are given together with the data source references. As seen from what is presented, very limited or no data are available for many of the cases. For each of such cases, the feasibility of data estimation and experimental determination has been studied. The results of this study are presented in a summary table at the end of each subsection for each property.

The summary table entitled "Availability of Experimental Data and Feasibility of Data Estimation and Measurement" gives results for each property of each material in four temperature ranges:

(1) Normal temperature,
(2) Normal temperature to 50° below melting point,
(3) 50° below melting point to melting point,
(4) Melting point to 20° above.

For each temperature range, the result is indicated by using one of the following codes:

D - Adequate data are available and data recommendation is possible.

D^- - Inadequate data are available and data estimation is possible.

V - No (or very limited) data are available but data estimation is possible.

V^- - No (or very limited) data are available and data estimation is possible only for limited range of temperature (and wavelength and surface condition if for a radiative property) or with larger uncertainty than required.

M^+ - No data are available and data estimation is impossible, but measurement using readily available technique and facility is possible.

M - No data are available and data estimation is impossible, but measurement using existing technique and facility is possible.

M^- - No data are available and data estimation is impossible, and modification of existing technique and/or facility is required for measurement.

N - No data are available and data estimation is impossible, and new technique and/or facility is required for measurement.

The results for the individual properties are presented separately in the following subsections.

A. Thermal Conductivity

1. Aluminum Alloy 2024

Experimental data on the thermal conductivity of aluminum alloy 2024-T4 are available up to 731 K. No data are available for the molten alloy.

Estimation of the thermal conductivity values for the solid near the melting point can be made by extrapolation based on the thermal conductivity curves of pure aluminum and other aluminum alloys.

Since this alloy contains about 93.5% aluminum, the ratio of the thermal conductivities of the solid and of the molten aluminum at the melting point, k_s/k_ℓ, may be used as a guide for the rough estimation of the thermal conductivity of this alloy in the molten state. However, the resulting values are uncertain and experimental determination may be required.

The temperature ranges of the available thermal conductivity data together with the data source references are given in the following table.

Thermal Conductivity of Aluminum Alloy 2024

Temperature Range (K)	Reference	Remarks
133-563	66998	Solid.
307-563	40017	Solid.
427-513	57400	Solid.
119-731	1075	Solid.
0-700	34753	Compiled data.

2. Aluminum Alloy 7075

Experimental data on the thermal conductivity of aluminum alloy 7075-T6 are available up to 700 K and can be extrapolated to the melting point without large uncertainty.

No information is available for the molten alloy. Since this alloy contains about 90% aluminum, the ratio of the thermal conductivities of the solid and of the liquid aluminum at the melting point, k_s/k_ℓ, may be used as a guide for the rough estimation of the thermal conductivity of this alloy in the molten state. However, the resulting values are uncertain and experimental determination may be required.

The temperature ranges of the available thermal conductivity data together with the source references are given in the following table.

Thermal Conductivity of Aluminum Alloy 7075

Temperature Range (K)	Reference	Remarks
117-702	6940	7075-T6.
311-700	23881	Not original.
117-700	9736	Density, thermal expansion coefficient, specific heat, and thermal diffusivity also reported.
117-622	16987	
273-573	10106	7075-T6.
28-700	34753	Compiled data.

3. Titanium Alloy 6Al-4V

Thermal conductivity and electrical resistivity data for this alloy have been reported up to about 1144 K and 1256 K, respectively. However, most of the data are from company literature and, therefore, they are only nominal values.

One way to obtain estimates of the thermal conductivity values of the solid near the melting point is to extrapolate the thermal conductivity curve to the melting point following the thermal conductivity curve of pure titanium. The extrapolation can be done reasonably well by adjusting the thermal conductivity values to be consistent with the electrical resistivity values extrapolated in a similar way. At 1089 K the thermal conductivity of this alloy differs only by about 25% from that of pure titanium. The difference between them might decrease further at higher temperatures. Therefore, the extrapolated thermal conductivity values near the melting point will be fairly reasonable and the uncertainties will be within about 10%.

No information is available for the thermal conductivity of this alloy in the molten state. Rough estimates might be obtained by assuming that k_s/k_ℓ of this alloy at the melting point is the same as that of pure titanium, which, however, is also a rough estimate.

The temperature ranges of the available data on the electrical resistivity and thermal conductivity of this alloy are given in the following two tables.

Electrical Resistivity of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
311-1256	90001	Compiled data.
293-1173	90002	$\Delta R/R_0$ reported.

Thermal Conductivity of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
311-811	9951	Electrical resistivity reported.
422-922	31540	
300-1144	34753	Literature data reported including those on density and specific heat.
293-1144	10941	Nominal values from a company bulletin.
33-1089	16736	Compiled data.

4. Hadfield Manganese Steel

Experimental data on the thermal conductivity of Hadfield steel are available from 100 to 1106 K. No data are available for the molten steel. Thermal conductivity of Hadfield steel may be extrapolated to the melting point with some uncertainty.

No electrical resistivity data are available for this steel. However, electrical resistivity data are available for steels of weight percent ratio Mn/Fe of 15/85 and various amount of carbon in a temperature range of 1273-1773 K.

The temperature ranges of the available thermal conductivity data together with the data source references are given in the following table.

Thermal Conductivity of Hadfield Manganese Steel

Temperature Range (K)	Reference	Remarks
100-500	9369	13.50 Mn, 1.12 C.
449	16299	
373-673	6719	13.50 Mn, 1.12 C.
324-1106	9353	

5. Boron Fiber Aluminum Metal Matrix Composite

No thermal conductivity data are available for these composite materials. TEPIAC may possibly be able to estimate the thermal conductivity of these composite materials theoretically from the data for the components.

6. Boron Fiber Epoxy Composite

The decomposition temperature of boron fiber epoxy composite has not been reported. Boron melts at 2573 K and epoxy resin starts to decompose at about 600 K.

Thermal conductivity data for a sample of this composite are available in the low temperature range between 67 and 317 K. No data are available at high temperatures and in liquid state. Experimental measurement is therefore necessary.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Boron Fiber Epoxy Composite

Temperature Range (K)	Reference	Remarks
67-317	90029	Compiled data; in the longitudinal and transverse directions and in the direction perpendicular to the ply surface.

7. Graphite Fiber Aluminum Metal Matrix Composite

No thermal conductivity data are available for these composite materials. TEPIAC may possibly be able to estimate the thermal conductivity of these composite materials theoretically from the data for the components.

8. Graphite Fiber Epoxy Composite

The decomposition temperature of graphite fiber epoxy resin composite has not been reported. Graphite sublimates between about 3925 and 3970 K and epoxy resin starts to decompose at about 600 K.

The available thermal conductivity data on this composite material is quite limited. So far four papers were found which contain some thermal conductivity data.

Compiled nominal thermal conductivity of graphite fiber epoxy composite is reported in [43475] from room temperature to about 2500 K. Epoxy resin decomposes at approximately 590 K, losing about 80% of its initial weight at 700 K. Therefore, partial decomposition occurs for graphite fiber epoxy composite between these temperatures. The thermal conductivity curve of graphite fiber epoxy composite has a steep negative slope between 590 and 700 K where the virgin and charred portions of the curves are connected.

It was mentioned that the thermal conductivity of graphite fiber epoxy composite is quite similar to that of graphite-phenolytic resin composite [43475]. The thermal conductivity is more dependent on lamination angles than on the resin or graphite fiber content in general.

Reference [53098] reports the thermal conductivity values of graphite fiber composite with various resin weight fractions which are predicted by employing a modified series/parallel model [90003].

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Graphite Fiber Epoxy Composite

Temperature Range (K)	Reference	Remarks
319-502	41719	E-1200 epoxy resin 100 parts, electrode graphite (filler) 100 to 200 parts, ethylenepolyamine (hardener) 8 parts by weight.
298-2500	43475	Compiled nominal value.
25-301	57598	60 wt.% fiber; in circumferential and longitudinal orientations of fiber.

9. Acrylic Resins

For some acrylics including polyethylmethacrylate and other copolymers, TEPIAC may possibly be able to generate estimated values for the thermal conductivity in solid state with confidence and in liquid state with larger uncertainty based on the data for polymethylmethacrylate (Lucite).

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Acrylic Resins

Temperature Range (K)	Reference	Remarks
93-423	55642	Polyethylmethacrylate.
93-298	55642	Poly n-butylmethacrylate.
123-298	55642	Polymethylacrylate.
123-298	55642	Polyethylacrylate.
123-298	55642	Copolymer of methylacrylate with 9 mol % of methyl-methacrylate.
123-323	55642	Copolymer of methylacrylate with 27 mol % of methyl-methacrylate.
123-373	55642	Copolymer of methylacrylate with 67 mol % of methyl-methacrylate.
93-423	55642	Copolymers of polyacrylonitriles with 18, 35, and 55 mol % of methyl-methacrylate.

Thermal Conductivity of Acrylic Resins (continued)

Temperature Range (K)	Reference	Remarks
93-423	55642	Polyacrylinitrile (smoothed value).
283-453	51010	Polyacrylonitrile (nitron).
263-418	69732	Copolymers of PMMA with 9.9 and 24.6 mol.% of Tri-n-propyl-tin-methacrylate.
113-423	62315	PMMA cross-linked with triallyl-cyanurate at concentrations of 0, 1, 5, 7, and 10 wt.%.
298	40390	Polyacrylic acid and some of its salts (H, Na, Cu, Hg).

10. Lucite

"Lucite" is a trade name of DuPont for polymethylmethacrylate (PMMA). The other trade name is "Plexiglass" for Rohm & Haas. The softening points of PMMA is 397 K [90004].

Polymethylmethacrylate (PMMA) has been the most extensively studied among acrylic resins for which thermal conductivity versus temperature has been measured. There are plenty of thermal conductivity data for PMMA from 0.4 to 510 K except the region between 23 and 78 K. Therefore, TEPIAC can recommend the thermal conductivity of PMMA for both solid and liquid state with confidence. The glass transition temperature of PMMA has been reported as 78 C [45197], 105 C [70966], and 112 C [69732]. Thermal conductivity of PMMA increases below the glass transition temperature and decreases above it.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of PMMA

Temperature Range (K)	Reference	Remarks
188-332	6567	Plexiglass.
303-433	29965	Plexiglass.
313.2	54021	Plexiglass and Lucite.
173-507	46013	Melted Plexiglass; under a pressure of 30 kP/cm^2 and 1 atm; thermal conductivity of melted polystyrene and polyamid also reported.
398-503	34122	PMMA.

Thermal Conductivity of PMMA (continued)

Temperature Range (K)	Reference	Remarks
0.4-510	70966	PMMA; compiled data; glass transition temperature reported as 105 C.
308-453	45197	PMMA; glass transition temperature reported as about 78 C.
263-418	69732	PMMA; glass transition temperature reported as 112 C.
273-431	56951	Plexiglass.
293-368	72192	PMMA with various kaolin (filler) concentration.

11. Polycarbonate Plastics

Plenty of thermal conductivity data are available for polycarbonate plastics from room temperature to 423 K. The thermal conductivity of polycarbonate plastic increases almost linearly with temperature. Thus, the extrapolation of thermal conductivity up to the softening point, 428 K, can be made. There seems no way to estimate the thermal conductivity of polycarbonate beyond 428 K.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Polycarbonate Plastics

Temperature Range (K)	Reference	Remarks
293-371	25875	Lexan.
169-242	41551	Prepared from Lexan resin.
298	40338	Compiled data.
288-373	43808	
298	59444	k vs pressure.
73-423	34122	Good experimental data.
293-403	36391	
Below glass-transition temperature	30573	Linear thermal expansion coefficient data also reported.
288-368	33630	Lexan.
295-375	44519	Polydiallyclycol carbonate.

12. Silicone Resins

Thermal conductivity data for most silicone resins, silicone rubbers, and silicone laminates are available at room temperature. Typical thermal conductivity values for sprayable silicone based ablator (Martin MA-25S) are available from 378 to 922 K.

For silicone resin coating, TEPIAC can generate recommended values from room temperature to about 550 K with confidence and can possibly extend up to the heat distortion temperature (about 760 K). For silicone glass laminates, TEPIAC can generate recommended values from room temperature to about 700 K with confidence and can possibly extrapolate to the heat distortion temperature. For silicone rubbers, TEPIAC can generate recommended values from room temperature up to 620 K.

The temperature ranges of the available data together with the data source references are given in the following three tables.

Thermal Conductivity of Silicone Resins

Temperature Range (K)	Reference	Remarks
298	19366	R-65; poly(vinyl) siloxane by Union Carbide and R-752; poly(vinyl) siloxane by Dow Corning.
298	57093	Polyethylsiloxane, polymethylsiloxane, and polymethylphenylsiloxane.
256-528	36145	Dow Corning DC 2106 silicone resin casting.
293-443	36391	KM-9 silicone polymer.
311-714	29617	Dow Corning Silicone Resin Molding-Compound 301; specific heat and thermal diffusivity data also reported.
319-622	35530	Filled silicone resin; 70% by weight of Dow Corning Sylgard 182 Resin, 14% by weight of Emerson and Cuming Inc. SI grade Eccspheres, 9% by weight of Union Carbide Phenolic Microballoons (BJO-0930), and 7% by weight of Sylgard 182 curing agent (catalyst).
378-922	58327	Sprayable silicone-based ablator (Martin MA-25S); ablative coatings for space research vehicles.

Thermal Conductivity of Silicone Rubbers

Temperature Range (K)	Reference	Remarks
478-617	23607	Raybestos Manhattan SR1056 Silicone Rubber.
298	51891	Silicone rubber; k vs edge insulation thickness.
323-338	44891	Silicone rubber.
300-308	47284	Silicone rubber.
283-325	35864	General Electric Type RTV-60 Silicone rubber (Silicone Elastomer).
89-572	34753	Chem Seal 3802 Silicone Rubber (RTV silicon rubber); specific heat data also reported.
288-438	56951	Silicone rubber.

Thermal Conductivity of Silicone Laminates

Temperature Range (K)	Reference	Remarks
478-700	23607	Phenolic G-7 Silicone laminate.
311-644	29617	Silicone glass laminate G-7; specific heat and thermal diffusivity also reported; for guided missiles.
339-611	35530	Filled silicone resin in phenolic-glass honeycomb (1/4 inch size cell); type HRP (GF11 cloth) of Hexcel Product, Inc.
228-689	37499	30% Sc 1013 phenyl Silane (Monsanto)-X994 glass (Owens Corning); ESM 1001P, ESM 1004BP, and NASA 602 G-H/C-S.

13. Aluminum Oxide (Wesgo Al-300)

The melting point of Wesgo Al-300 aluminum oxide has not been reported, but it might be close to but lower than that of pure Al_2O_3, 2326 K. Wesgo Al-300 has been reported as a fired alumina with the composition of 97.55 Al_2O_3, 1.35 SiO_2, 1.05 CaO, 0.03 Fe_3O_4, and 0.02 Na_2O.

Experimental data on the thermal conductivity of Al-300 are available from 373 to 1273 K. TEPIAC has recommended values for 99.5% pure, 98% dense polycrystalline Al_2O_3 up to the melting point [61232]. At 373 K the thermal conductivity of Al-300 is about 40% lower than the thermal conductivity of 99.5% pure Al_2O_3 polycrystal. As

temperature increases the thermal conductivity value of Al-300 and that of 99.5% Al_2O_3 become close to each other.

Therefore, based on the recommended thermal conductivity for 99.5% pure Al_2O_3 polycrystal, the thermal conductivity of Wesgo Al-300 can possibly be extended up to the melting point and down to room temperature.

No information is available for the molten Al-300 and there is no way to estimate it at the present time.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Wesgo Al-300 Aluminum Oxide

Temperature Range (K)	Reference	Remarks
473-973	31786	97.6 Al_2O_3.
373-1273	28172	Alumina cubes used as reference standard.
419-1225	35041	Porosity 5%.
452-973	10682	

14. Boron Nitride

The sublimation temperature has been reported as 2730 C (3003 K) for commercial BN and 3000 C (3273 K) for pure BN at 1 atm [52914].

Boron nitride is an interesting material which can have a hexagonal structure very similar to that of graphite. Hot pressed boron nitride is anisotropic and possesses both relatively high thermal conductivity and low thermal expansion coefficient. Different authors have reported thermal conductivity data in the direction parallel or perpendicular to rod axis, a-axis, or moulding direction. According to the results of Bourdeau [27012], the thermal conductivity of BN in the direction parallel to a-axis is almost 200 times higher than that in the direction parallel to c-axis. Therefore, it is necessary to report whether the thermal conductivity data are for polycrystal or single crystal with direction of measurement specified. Most of existing high-temperature data are for the polycrystal.

Extrapolation to near the sublimation temperature may be possible using the general shape of the thermal conductivity curves of nitrides as a guide. However, the uncertainty will be high.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Boron Nitride

Temperature Range (K)	Reference	Remarks
1047-2129	26008	Hot pressed.
298-1033	27012	Along a-axis and c-axis.
573-1273	47961	Hot pressed electrical resistivity also reported.
454-1651	52260	Commercially pure.
473-1073	10692	Porosity 16%.
573-2073	70392	
523-1473	58910	Parallel and perpendicular to the pressing direction.
298	46081	
298	66442	Pyrolytic BN.
100-800	64510	Parallel and perpendicular to deposition plane of pyrolytic BN.

15. Calcium Aluminum Silicate (Corning 9753)

The Corning 9753 is a solid solution having a composition of 30% CaO - 40% Al_2O_3 - 30% SiO_2. No paper was found that contained thermal conductivity data for Corning 9753. Therefore, experimental measurement and further research are necessary.

A German paper [28664] contains information about the melting temperature and thermal conductivity of a ternary system of CaO, Al_2O_3, and SiO_2. According to that paper the melting point of 30% CaO - 40% Al_2O_3 - 30% SiO_2 is between 1723 and 1773 K. Thermal conductivity was measured from 473 to 1673 K for 50% SiO_2 - 40% Al_2O_3 - 10% CaO, 90% SiO_2 - 7% Al_2O_3 - 3% CaO, 3% SiO_2 - 95% Al_2O_3 - 2% CaO, 50% SiO_2 - 40% Al_2O_3 - 10% CaO, and 8% SiO_2 - 12% Al_2O_3 - 15% CaO. Thermal conductivity values are between 0.410-1.34 k cal/m h °C and are increasing with temperature.

This information might be helpful for future experimental work.

16. Magnesium Fluoride (Kodak IRTRAN 1)

The melting point of magnesium fluoride is about 1583 K [68232]. Experimental data on thermal conductivity of magnesium fluoride are available from room temperature to 1177 K. However, these data are not for IRTRAN 1 by Kodak.

The radiative thermal conductivity of MgF_2 seems not insignificant above 1000 K. When the thermal conductivity is extrapolated to above 1177 K the radiative component should be considered.

No information is available for molten MgF_2. TEPIAC has compiled the thermal conductivity data for molten LiF [49151]. The thermal conductivity of molten MgF_2 may possibly be roughly guessed based on the experimental data for molten LiF.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Magnesium Fluoride

Temperature Range (K)	Reference	Remarks
303-973	45277	
301-1177	52938	Hot pressed.
727	25656	Hot pressed.

17. Pyroceram (Corning 9606)

The thermal conductivity of Pyroceram 9606 has been studied and reviewed by NBS group [45435, 37328, 32722, and 29152] as a thermal conductivity reference standard. Experimental data on the thermal conductivity of Pyroceram 9606 are available up to about 1400 K and possibly can be extrapolated to the softening point of about 1623 K.

No information is available for the molten state and it seems almost impossible to estimate theoretically the thermal conductivity of molten Pyroceram. Experimental determination is therefore necessary.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Pyroceram 9606

Temperature Range (K)	Reference	Remarks
298	60590	Measured by the flash technique.
298	29925	Nominal value.
298	8100	Nominal value.
273-1057	36468, 57665	Data measured by NBS also reported.
80-1400	45435	Studied as a thermal conductivity reference standard.

Thermal Conductivity of Pyroceram 9606 (continued)

Temperature Range (K)	Reference	Remarks
80-1273	37328	
473-1273	32722	
273-873	29152	
273-1173	32162	Specific heat data also reported.
273-873	49933	

18. Silica (Fused)

The melting point of fused silica is about 1996 K. Experimental data on the thermal conductivity of fused silica are available up to 1513 K. Thermal conductivity values for high-purity transparent fused silica have been recommended by TPRC [90005] up to 1400 K. No information is available for molten silica.

Estimation up to the melting point of fused silica could possibly be made by using T^3 dependence due to the radiative component which is predominant at high temperatures. This component is, however, dependent on transparency and sample size of the fused silica. The uncertainty of the estimated values will be higher than 30% near the melting point.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Silica (Fused)

Temperature Range (K)	Reference	Remarks
0-1400	90005	Published by TPRC.
1513	59827	
89-1522	34753	Compiled data.

19. Silicon

Silicon melts at about 1685 K. The thermal conductivity of pure silicon has been recommended by TPRC [90006] up to near the melting point, and EPIC [56727] has compiled the existing data for the electronic properties and thermal conductivity of silicon from 100 to 1400 K.

The thermal conductivity of molten silicon near the melting point has been reported by Mil'vidskii and Eremeev [37663] as 2.09 W cm^{-1} K^{-1} and by Shashkov and Grishin

[31379] as 0.669 W cm^{-1} K^{-1}. Since these two values differ by a factor of 3, it is very difficult to recommend the thermal conductivity of molten silicon. However, the result for solid silicon of Shashkov and Grishin [31379] is more close to the recommended value of TPRC [90006] and is more realistic. The ratio of the thermal conductivities of the solid and of the molten silicon at the melting point, k_s/k_ℓ, of Shashkov and Grishin can be used to estimate the thermal conductivity of molten silicon from the thermal conductivity of solid silicon recommended by TPRC. The uncertainty of the estimated values might be larger than 40%.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Silicon

Temperature Range (K)	Reference	Remarks
1-1685		Values recommended by TPRC.
100-1400	56727	Compiled by EPIC.
1685	37663, 35369	Solid and liquid state.
1685	31379, 31572	Solid and liquid state.

20. Silicon Carbide

Detailed information on SiC has been reviewed and given in [38524, 34058, and 63346].

Several technological methods exist for obtaining silicon carbide. Materials obtained by different production schemes vary in chemical composition, porosity, structural mechanical features, phase composition, texture, etc. Any of the characteristics will markedly influence the numerical value of the thermal conductivity. Therefore, the literature data are widely divergent.

Experimental data on the thermal conductivity of silicon carbide in bulk form are available from room temperature to 2071 K. Extrapolation to the melting point can possibly be made. No data are available for silicon carbide in chemical vapor deposited coating form.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Silicon Carbide

Temperature Range (K)	Reference	Remarks
889-1801	6970, 6477	Density 3.1 g cm^{-3}.
404-1582	7180	Density 2.18 g cm^{-3}.
298-873	71169	Unirradiated and irradiated samples.
50-1700	70467	Extrapolated data.
473-1373	37569	
473-1673	38524	Compiled data.
1537-2071	61239	Doubtful validity.

21. Silicon Nitride

Density values of Si_3N_4 samples for which thermal conductivity data have been reported vary from about 2.0 to 3.0 g cm^{-3}. The thermal conductivity of Si_3N_4 varies very significantly with density of the samples. For example, the thermal conductivity of Si_3N_4 at 1300 K with density of 2.5 g cm^{-3} is three times higher than that of Si_3N_4 with density of 2.01 g cm^{-3}. Therefore, unless the density of Si_3N_4 is specified, TEPIAC has to recommend the thermal conductivity of Si_3N_4 as a function of density, in addition to temperature.

Since the dense Si_3N_4 dissociates and evaporates at about 2173 K, there is no way to obtain the thermal conductivity data above the dissociation temperature. The result of Neel et al. [26074] for Si_3N_4 with density of 2.38 g cm^{-3} is the only one measured up to near the dissociation temperature. Since the thermal conductivity versus temperature curve of Si_3N_4 is quite smooth, TEPIAC can possibly generate a set of the thermal conductivity values for Si_3N_4 as a function of density from room temperature to near the dissociation temperature.

No information is available for Si_3N_4 in chemical vapor deposited coating form.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Conductivity of Silicon Nitride

Temperature Range (K)	Reference	Remarks
303	25061	Density 2.34 and 3.16 g cm^{-3}.
303	68819	Si_3N_4-SiC composite system (0-0.4 volume fraction of SiC phase in Si_3N_4 matrix).

Thermal Conductivity of Silicon Nitride (continued)

Temperature Range (K)	Reference	Remarks
1088-1719	50954	15 samples with densities varying from 2.01 to 2.5 g cm^{-3}.
603-2061	26074, 24856	Density 2.38 g cm^{-3}.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Thermal Conductivity*

Material	Normal Temperature	Normal Temp. to 50° below M.P.	50° below M.P. to M.P.	M.P. to 20° above
1. Al Alloy 2024	D	D⁻	V	V⁻, M
2. Al Alloy 7075	D	D⁻	V	V⁻, M
3. Ti Alloy 6Al-4V	D	D⁻	V	M⁻
4. Hadfield Manganese Steel	D	D⁻	V⁻	M⁻
5. Boron fiber aluminum metal matrix composite	M	M	M	M
6. Boron fiber epoxy composite	D	D⁻	N	N
7. Graphite fiber aluminum metal matrix composite	M	M	M	M
8. Graphite fiber epoxy composite	D	D⁻	N	N
9. Acrylic resins**	D	D⁻	V	M
10. Lucite	D	D	D	D⁻
11. Polycarbonate plastics**	D	D	D⁻	M
12. Silicone resins**	D	D⁻	V⁻	M
13. Aluminum oxide (Wesgo Al-300)	V	D⁻	V⁻	M⁻
14. Boron nitride	D	D⁻	V⁻	N
15. Calcium aluminum silicate (Corning 9753)	M	M	M	M⁻
16. Magnesium fluoride (Kodak IRTRAN 1)	D⁻	V⁻	V⁻	M⁻
17. Pyroceram (Corning 9606)	D	D⁻	V	M
18. Silica (fused)	D	V⁻	V⁻	M
19. Silicon	D	D	D	D⁻, N
20. Silicon carbide	D⁻	D⁻	V⁻	N
21. Silicon nitride	D⁻	D⁻	V	N

* See the explanation of codes on page 4.

** The available data are for some specific materials only.

B. Thermal Diffusivity

1. Aluminum Alloy 2024

No data are available for the liquid state. In solid state, one measurement by Cushman [41154] was made up to 750 K, close to the solidus temperature. The solid-state value at melting point can be obtained by extrapolation. To obtain the thermal diffusivity of this alloy in liquid state, one of the following three methods may be applicable.

(1) If the thermal conductivity for the liquid state is known, then the diffusivity may be calculated from the thermal conductivity, specific heat, and density. Usually these data are not available, but for specific heat and density the values for the alloy may be calculated from that of each of the component element with reasonable reliability, more reliable than those for the solid state, by the simple additive formula:

$$P_a = \sum_i c_i P_i \tag{1}$$

where P_i indicates the property of the ith component and c_i is its concentration in the alloy. Even the thermal conductivity values in liquid state may be calculated using a formula similar to the one given by Filippov et al. [90030] :

$$k_a = \sum_i c_i k_i - \frac{1}{2} \sum_{i,j} 0.72\, k_i - k_j\, c_i\, c_j \tag{2}$$

though the accuracy of the result is questionable.

(2) We may correlate the values of α_s/α_ℓ of the elements at the melting point, then generate a simple relation for the alloy and calculate the value in the liquid state from the known solid state value. This method cannot generate values beyond the immediate neighborhood of the melting point.

(3) Thermal diffusivity values may be calculated from a formula similar to Eq. (2). Actually, all three methods may be used to complement each other to obtain the best result.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Aluminum Alloy 2024

Temperature Range (K)	Reference	Remarks
372-749	41154	
313-698	6693	
116-700	9736	
273-573	23608	

2. Aluminum Alloy 7075

No data are available for the liquid state. For the solid state, no data are available above 793 K. To obtain values beyond this temperature, the same methods as those discussed in the preceding subsection on Aluminum Alloy 2024 may be used.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Aluminum Alloy 7075-T6

Temperature Range (K)	Reference	Remarks
348.2	6693	
373-643	6693	
348-793	6693	
348, 473	6693	
348-633	6693	
373-603	6693	
513, 653	6693	
473, 673	6693	
348, 583	6693	
773, 783	6693	
116-700	9736	Calculated from measured thermal conductivity, specific heat, and density.
144-700	9736	Same as above.

3. Titanium Alloy 6Al-4V

In solid state the thermal diffusivity of this alloy has been measured up to 1183 K, about 740 K below the melting point. No data are available for the liquid state. For extrapolation of data to higher temperatures and for estimation of values for the molten alloy, the same methods as those discussed in the subsection on Aluminum Alloy 2024 may be used.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
398-1118	6693	
448-1023	6693	
373-1183	6693	

4. Hadfield Manganese Steel

No data are available for this steel. Values may be estimated by using the methods described in the subsection on Aluminum Alloy 2024.

5. Boron Fiber Aluminum Metal Matrix Composite

No data are available for this composite material. The solid-state thermal diffusivity values may be estimated from that of the individual constituent materials, or from the thermal conductivity, specific heat, and density of the individual constituent materials. It may be possible to estimate the values in liquid state by correlation, but the accuracy would be questionable.

The temperature ranges of some of the available data for aluminum together with the data source references are given in the following table.

Thermal Diffusivity of Aluminum

Temperature Range (K)	Reference	Remarks
340-829	15663	99.97 pure.
295-408	24813	
326-799	27539	
293-1073	70153	In solid and liquid states.
1-8000	53600	Calculated.

6. Boron Fiber Epoxy Composite

There are no data available for this composite material. In the solid state, the thermal diffusivity of this composite may be estimated from that of the individual constituents. No experimental data are available for boron either. But Powell et al. [53600] calculated the thermal diffusivity of boron from 50 to 1500 K using the selected values of

specific heat and density and the TPRC recommended values of thermal conductivity. It is perhaps better to calculate the thermal conductivity, specific heat, and density of the composite first from those property values of the individual constituents, and then to derive the thermal diffusivity of the composite from the calculated values. The generated values may be extrapolated to the melting point. Above melting point, there is no conceivable way to estimate the values with certainty since the information on molten epoxy is completely lacking.

7. Graphite Fiber Aluminum Metal Matrix Composite

No data are available for this composite material. The solid-state thermal diffusivity values may be estimated in the same way as that for the above composite materials. The values for the liquid state may also be estimated by correlation with questionable accuracy.

8. Graphite Fiber Epoxy Composite

No data are available for this composite. However, there are data for the base materials graphite and epoxy. A method may be devised to calculate the thermal diffusivity of the composite using the values of the individual base materials. It may also be possible to calculate the thermal conductivity, specific heat, and density of the composite from those of the individual constituents first, and then to derive the thermal diffusivity from the calculated thermal conductivity, specific heat, and density. No data are available near and above the melting point for either graphite or epoxy. Probably some estimation can be made but the accuracy would be very questionable.

The temperature ranges of some of the available data for graphite and for epoxy together with the data source references are given in the following tables.

Thermal Diffusivity of Graphite

Temperature Range (K)	Reference	Remarks
385-936	16037	Type cs.
520-941	29500	
311-1466	27009	
1188-3038	28899	U.B. carbon "A".
303-2240	45528	Pyrolytic graphite.
1072-3085	54195	SX-5.

Thermal Diffusivity of Epoxy Resin

Temperature Range (K)	Reference	Remarks
298-363	21077	
293-443	34666	
293-373	56593	Amorphous, in glassy state.

9. Acrylic Resins

The available data are inadequate for the acrylic resins. A couple of measurements were made from room temperature to 573 K. These thermal diffusivity values may possibly be extrapolated to the melting point. It will be difficult to estimate values for the liquid state.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Acrylic Resins

Temperature Range (K)	Reference	Remarks
r.t.	44457	
323-573	57533	

10. Lucite

No data are available beyond the solidus point. For the solid state, the available data are inadequate, but estimation of values up to the melting point may be possible.

The temperature ranges of some of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Lucite

Temperature Range (K)	Reference	Remarks
r.t.	35467	
323-348	35542	
293-383	36391	
r.t.	45138	
308	47246	
20-325	64171	
r.t.	67963	

11. Polycarbonate Plastics

Data are available for both solid and liquid states. The temperature ranges of some of the data together with the data source references are given in the following table.

Thermal Diffusivity of Polycarbonate Plastics

Temperature Range (K)	Reference	Remarks
391-545	30383	In solid and liquid states.
293-393	36391	
169-304	41551	
300-427	41846	

12. Silicone Resins

No data are available for the liquid state. For the solid state, the data are reported up to 573 K. There will be no problem to extrapolate the values to the melting point. However, it is not possible to estimate the liquid-state values.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Silicone Resins

Temperature Range (K)	Reference	Remarks
283-322	35864	Silicone rubber.
293-383	36391	Silicone rubber.
297-408	37387	Silicone rubber.
298-402	44457	Silicone rubber.
323-573	57533	Silicone rubber.

13. Aluminum Oxide (Wesgo Al-300)

No experimental data are available for this particular brand of aluminum oxide. However, there are plenty of data for other kinds of aluminum oxides which can be used to generate values for this material by certain adjustments coupling with correlation. For liquid state, an estimation of the values is not possible.

The temperature ranges of some of the available data of aluminum oxide together with the data source references are given in the following table.

Thermal Diffusivity of Aluminum Oxide

Temperature Range (K)	Reference	Remarks
1313-2153	36028	98% pure.
293-1388	24367	
298-1273	27922	
573-1623	42720	98.7% pure, 86.5% dense.
1773-2073	6931	99% dense.
295-1248	61777	
368-1692	45427	99.8% pure, 99% dense.
95-1419	44943	
1050-2080	54061	
1313-2063	56452	
803-2197	66734	
473-1073	62758	

14. Boron Nitride

One set of experimental data was found [47572] for this material. The temperature range of the measurement was 413 to 1423 K, far below the sublimation point, which is about 3273 K. The estimation of the liquid-state values is not necessary. In solid state, there should be no big problem for extending the values to the sublimation point with the help of the data of thermal conductivity, specific heat, and density.

15. Calcium Aluminum Silicate (Corning 9753)

No experimental data are available for this particular material. However, some conclusion might be drawn from the data of several other CaO-Al_2O_3-SiO_2 mixtures, although the accuracy would be questionable. No estimation of the values for the liquid state is feasible.

The temperature ranges of some of the available data for CaO-Al_2O_3-SiO_2 mixtures (solid solution) together with the data source references are given in the following table.

Thermal Diffusivity of CaO-Al_2O_3-SiO_2 Mixtures

Temperature Range (K)	Reference	Remarks
373-673	48703	49.4 SiO_2, 12.8 Al_2O_3, 7.2 CaO.
373-673	48703	46.2 SiO_2, 14.5 Al_2O_3, 12.1 CaO.
373-673	48703	45.1 SiO_2, 18.6 Al_2O_3, 12.6 CaO.

Thermal Diffusivity of $CaO-Al_2O_3-SiO_2$ Mixtures (continued)

Temperature Range (K)	Reference	Remarks
373-673	48703	48.1 SiO_2, 12.0 Al_2O_3, 23.0 CaO.
373-673	48703	55.3 SiO_2, 13.5 Al_2O_3, 17.6 CaO.
75-302	55639	50 Al_2O_3, 50 SiO_2.

16. Magnesium Fluoride (Kodak IRTRAN 1)

No experimental data are available for the liquid state. In the solid state, two measurements [49151, 52938] were made in the temperature range from 300 to 1177 K. The values can be extrapolated to the melting point. However, these values are not for IRTRAN 1. It is not possible to estimate the values for the liquid state.

17. Pyroceram (Corning 9606)

No experimental data are available for the liquid state. In the solid state, two measurements [49933, 25075] were made in the temperature range 298 to 1173 K. The values can be extrapolated to the melting point. Estimation of the values for the liquid state is not possible.

18. Silica (Fused)

There are no experimental data reported for the liquid state of fused silica. In the solid state, measurements were made up to 1223 K. It may be possible to extend the values by extrapolation or other means to the melting point. An estimation of the values for the liquid state is not possible.

The temperature ranges of some of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Silica (Fused)

Temperature Range (K)	Reference	Remarks
323-348	34599	
82-412	38402	
r.t.	40751	
153-1223	47289	
323-1023	54186	
335-1039	55839	
230-1100	71965	

19. Silicon

Experimental data are available up to 1375 K. Powell et al. [53600] calculated the thermal diffusivity values of silicon from 10 K to the melting point using the TPRC recommended thermal conductivity and selected values of specific heat and density. For the liquid state, the values may be estimated by correlation with questionable accuracy.

The temperature ranges of some of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Silicon

Temperature Range (K)	Reference	Remarks
310-1016	16983	
292-1375	29948	
311-1016	25053	
223-373	57247	
10-1683	53600	Calculated.

20. Silicon Carbide

Experimental data are available for the buck form up to 1673 K. The values can be extrapolated up to the sublimation (decomposition) point. The estimation of values at higher temperatures is not practical.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Diffusivity of Silicon Carbide

Temperature Range (K)	Reference	Remarks
353-1673	20600	
298	36698	

21. Silicon Nitride

No data are available for this material. It is expected that the thermal diffusivity values for the solid state in buck form can be derived from the thermal conductivity, specific heat, and density. No estimation of the liquid state values is necessary since the material sublimates at 2173 K.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Thermal Diffusivity*

Material	Normal Temperature	Normal Temp. to 50° below M.P.	50° below M.P. to M.P.	M.P. to 20° above
1. Al Alloy 2024	D	D⁻	V	V⁻
2. Al Alloy 7075	D	D⁻	V	V⁻
3. Ti Alloy 6Al-4V	D⁻	V	V	V⁻
4. Hadfield Manganese Steel	V	V⁻	V⁻	V⁻
5. Boron fiber aluminum metal matrix composite	V	V	V⁻	M
6. Boron fiber epoxy composite	V	V⁻	V⁻	M⁻
7. Graphite fiber aluminum metal matrix composite	V	V	V⁻	M
8. Graphite fiber epoxy composite	V	V⁻	V⁻	M⁻
9. Acrylic resins**	D⁻	D⁻	V	M⁻
10. Lucite	D⁻	D⁻	V	M⁻
11. Polycarbonate plastics**	D⁻	D⁻	D⁻	D⁻
12. Silicone resins**	D⁻	D⁻	V	M⁻
13. Aluminum oxide (Wesgo Al-300)	V	V	V	M⁻
14. Boron nitride	D⁻	V	V	N
15. Calcium aluminum silicate (Corning 9753)	M	M⁻	M⁻	M⁻
16. Magnesium fluoride (Kodak IRTRAN 1)	D⁻	V	V	M⁻
17. Pyroceram (Corning 9606)	D⁻	V	V	M⁻
18. Silica (fused)	D	V⁻	V⁻	M⁻
19. Silicon	D	D	V	M⁻
20. Silicon carbide	D⁻	V⁻	V⁻	N
21. Silicon nitride	V⁻	V⁻	V⁻	N

* See the explanation of codes on page 4.
** The available data are for some specific materials only.

C. Emittance

1. Aluminum Alloy 2024

Experimental data on the spectral emittance of Aluminum Alloy 2024 are available up to 383 K. No information is available for the molten alloy. The temperature and wavelength ranges of the available spectral emittance data together with the data source references are given in the following table.

Normal Spectral Emittance of Aluminum Alloy 2024

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
303, 383	7-15	20470	Flat and smooth surface.
301	2-21	21553	
323	0.2-27	29202	

2. Aluminum Alloy 7075

Experimental data on the spectral emittance of Aluminum Alloy 7075 are available up to 383 K. No information is available for the molten alloy. The temperature and wavelength ranges of the available spectral emittance data together with the data source references are given in the following table.

Normal Spectral Emittance of Aluminum Alloy 7075

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
303, 383	7-15	20470	Flat and smooth surface.
323	0.25-27	29202	3.2-4.4 μ roughness.
323	0.5-12	38291	Sand blasting surface.

3. Titanium Alloy 6Al-4V

Experimental data on the spectral emittance of titanium alloy are available up to 700 K. No information is available for the molten alloy.

The temperature and wavelength range of the available spectral emittance together with the data source references are given in the following table.

Normal Spectral Emittance of Titanium Alloy 6Al-4V

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
296, 700	0.5-15	68308	Anodized surface.

4. Hadfield Manganese Steel

No information is available for the spectral emittance of Hadfield Steel.

5. Boron Fiber Aluminum Metal Matrix Composite

No information is available.

6. Boron Fiber Epoxy Composite

No information is available.

7. Graphite Fiber Aluminum Metal Matrix Composite

No information is available.

8. Graphite Fiber Epoxy Composite

No information is available.

9. Acrylic Resins

No information is available for other acrylic resins except Lucite, for which see next subsection.

10. Lucite

Only room-temperature experimental data are available for the normal spectral emittance of Lucite, which is given below.

Normal Spectral Emittance of Lucite

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	0.2-2.6	32388	Indirect method.

11. Polycarbonate Plastics

No information is available.

12. Silicone Resins

No information is available.

13. Aluminum Oxide (Wesgo Al-300)

Experimental data on the spectral emittance of aluminum oxide are available up to 1600 K. No information is available for the liquid state.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Aluminum Oxide

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
873, 1303	1-14	16606	
873	1.01-14.9	21923	
810, 1591	1-15	29570	
1303, 1323	0.92-14	32045	
1273	1-15	35840	
373-1243	1-15	37398	
1400	2-14	38726	
1200-1600	1-15	41606	
298	1-15	48368	
1255	1-14.5	50298	
1300	1-10.01	35902	Al_2O_3 on steel substrate.
300-1074	1.21-14.88	46986	Al_2O_3 on stainless steel substrate.
300-1074	1.21-14.88	47262	Same data as reported in 46986.
1255	1-15	50298	Al_2O_3 on Inconel substrate.

14. Boron Nitride

Experimental data on the spectral emittance of boron nitride are available up to 2020 K.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Boron Nitride

Temperature Range (K)	Wavelength Range (μm)	References	Remarks
873-1353	1.5-14	16606	
1023	1-15	22272	Sintered sample.
1083	0.5-14.9	26088	Polished surface.
873, 1273	1-14.5	32045	
1280-2020	2.26-15	34724	
1300	1-10	35902	
1273	1-11	36117	
1273	1-11	37478	Same data as reported in 36117.

15. Calcium Aluminum Silicate (Corning 9753)

No information is available.

16. Magnesium Fluoride (Kodak IRTRAN 1)

Experimental data on the spectral emittance of magnesium fluoride are available up to 373 K. No information is available for the liquid state.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Magnesium Fluoride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	1.07-15.96	29641	Coating on SiO and Si substrate.
373	3.49-44.5	40450	
373	16-44	48368	Irtran 1

17. Pyroceram (Corning 9606)

Experimental data on the spectral emittance of pyroceram are available up to 1403 K. No information is available for the liquid state. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Pyroceram

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
813-1403	1-14	29570	

18. Silica (Fused)

Experimental data on the spectral emittance of fused silica are available up to 2050 K.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Silica (Fused)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
313	3-14	16961	
1273	1-15	35909	
588-922	2-9	36144	
863-1580	1-15	37424	
500	1-15	58981	
373	5-16	61457	Spectral Hemspherical emittance.
1750-2050	5	67865	
293-1023	2.8-11	68683	
300	0.4-3.5	36167	
300	4-13.5	36167	
300	5-16	42737	Coating.

19. Silicon

Experimental data on the spectral emittance of silicon are available up to 1346 K. No information is available for the liquid state at wavelength ranges from 1 to 12 μ. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Silicon

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
333-433	3-15	16961	Ground and polished surface.
298	1.18-15.97	29641	Solar cell.

Normal Spectral Emittance of Silicon (continued)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
323-473	1.94-24	32537	
816-1346	0.2-15	41640	
313-433	3-15	45697	
300-1074	2.6-35	47262	Optical polished and etched surface.
816-1346	0.2-15	56727	Unoriginal.
1033-1195	0.6-2.5	56874	
1095	1-2.5	56874	Coating on Al_2O_3.
1300	1-10	40101	
1353	2-7.5	49932	Hot pressed.
1093-1103	1-11	50806	
1093-1103	1-11	50987	Same as reported in 50806.
1280-2020	2.25-15	52914	Unoriginal.
1128, 1133	0.55-11	52946	
1300	1-10	35902	Coating, roughed and polished surface.

20. Silicon Carbide

Experimental data on the spectral emittance of silicon carbide are available up to 2500 K. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Silicon Carbide

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
1375	1.7-15	758	
1296	2.24-13.9	10461	
1223	1-15	22272	Sintered sample.
1358	0.65-14.9	25673	
873, 1273	1-14.5	32045	
2000-2500	0.6-14	62013	
813-1513	1-15	29570	Coating on Al_2O_3 substrate.
1173	1-15	46366	Flame sprayed coating.

21. Silicon Nitride

Experimental data on the spectral emittance of silicon nitride are available up to 1023 K. No information is available for the liquid state. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Normal Spectral Emittance of Silicon Nitride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
1023	1-15	22272	Sintered sample.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Emittance*

Material	Normal Temperature	Normal Temp. to 50° below M.P.	50° below M.P. to M.P.	M.P. to 20° above
1. Al Alloy 2024	D^-	V^-, M^+	M	M
2. Al Alloy 7075	D^-	V^-, M^+	M	M
3. Ti Alloy 6Al-4V	D^-	V^-, M^+	M	M
4. Hadfield Manganese Steel	M^+	M^+	M	M
5. Boron fiber aluminum metal matrix composite	M^+	M	N	N
6. Boron fiber epoxy composite	M^+	M	N	N
7. Graphite fiber aluminum metal matrix composite	M^+	M	N	N
8. Graphite fiber epoxy composite	M^+	M	N	N
9. Acrylic resins	M^+	M^+	M	M
10. Lucite	V^-, M^+	M^+	M	M
11. Polycarbonate plastics	M^+	M^+	M	M
12. Silicone resins	M^+	M^+	M	M
13. Aluminum oxide (Wesgo Al-300)	D	V^-, M	M	N
14. Boron nitride	D	V^-, N	N	N
15. Calcium aluminum silicate (Corning 9753)	M^+	M	M	N
16. Magnesium fluoride (Kodak IRTRAN 1)	D^-	M	M	N
17. Pyroceram (Corning 9606)	D^-	V^-, M	M	N
18. Silica (fused)	D	V^-, M	M	N
19. Silicon	D	V, M	M	N
20. Silicon carbide	D	V^-, M	N	N
21. Silicon nitride	D	V^-, M	N	N

* See the explanation of codes on page 4.

D. Reflectance

In presenting the information on the available experimental data, the details pertaining to the conditions under which the spectral reflectance was measured are reported in the table for the appropriate material. The geometry of the measurement is reported under the "Remarks" column of the table. The angle θ is the angle of the incident radiation relative to the normal to the sample surface, the angle θ' is the angle of the reflected radiation also relative to the normal to the sample surface, and ω' is the solid angle through which the reflected radiation is measured. Thus, the data are for normal spectral reflectance if θ is equal or approximately equal to zero, or for hemispherical spectral reflectance if ω' is equal to 2π.

1. Aluminum Alloy 2024

No information is available.

2. Aluminum Alloy 7075

No information is available.

3. Titanium Alloy 6Al-4V

Data are reported for normal temperature but only over part of the wavelength range of interest. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Spectral Reflectance of Titanium Alloy 6Al-4V

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
~300	1-2.7	10017	Surface conditions for which measurements were made are as follows: as received, cleaned, oxidized, and polished; $\theta = 9^\circ$, $\omega' = 2\pi$.

4. Hadfield Manganese Steel

No information is available.

5. Boron Fiber Aluminum Metal Matrix Composite

No information is available.

6. Boron Fiber Epoxy Composite

No information is available.

7. Graphite Fiber Aluminum Metal Matrix Composite

No information is available.

8. Graphite Fiber Epoxy Composite

No information is available.

9. Acrylic Resins

No information is available for other kinds of acrylic resin except Lucite, for which see the next subsection.

10. Lucite

Data are reported for normal temperature but only over the lower portion of the wavelength range of interest. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Spectral Reflectance of Lucite

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
~298	0.242–2.60	32388	Lucite (approx. 1/8 in. thick); reported error $\leq 5\%$; $\theta = 0^\circ$, $\omega' = 2\pi$.

11. Polycarbonate Plastics

No information is available.

12. Silicone Resins

No information is available.

13. Aluminum Oxide (Wesgo Al-300)

No information is available.

14. Boron Nitride

Data are reported for normal temperature over the entire wavelength range of interest. See the table for details. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Spectral Reflectance of Boron Nitride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	0.23-2.65	22272	100% pure; sintered at 2123 K for 2 hrs; density 2.00 g cm^{-3} (theoretical density 2.27 g cm^{-3}); MgO reference standard; θ approx. 0° and $\omega' = 2\pi$.
298	2.0-35.9	37886	Pressed powder; $\theta = 0^\circ$ and $\omega' = 2\pi$.
~298	0.230-2.65	37398	99.5% pure powder from Carborundum Corp.; mesh size 325; nine curves presented as a function of compaction pressure which varied from 290 to 34,600 psi; MgO reference standard; θ approx. 0° and $\omega' = 2\pi$.
~298	1-15	37398	Commercially sintered sample; three curves presented as a function of surface roughness: from 35-40 μ in., 300-400 μ in., and 1800-2200 μ in.; $\theta = 0^\circ$ and $\omega' = 2\pi$.
~298	5.00-33.3	39203	Hexagonal crystal; light parallel to c-axis of crystal; θ approx. 0° and θ' approx. 0°.
313	2.2-46	51145	Synthetic polycrystal, 6.0 mm thick; flat to 10 fringes or better; aluminum mirror reference standard; both θ and θ' are 30°.

15. Calcium Aluminum Silicate (Corning 9753)

No information is available.

16. Magnesium Fluoride (Kodak IRTRAN 1)

Data are reported for normal temperature over most of the wavelength range of interest. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Spectral Reflectance of Magnesium Fluoride (IRTRAN 1)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
~298	2.0-50.0	30100	2 mm thick specimen; aluminum mirror reference standard; both θ and θ' = 30°.

17. Pyroceram (Corning 9606)

Data are reported for normal temperature over the lower portion of the wavelength range of interest. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Spectral Reflectance of Pyroceram (Corning 9606)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	0.297-2.72	10060	Reported error 4%; $\theta = 9°$ and $\omega' = 2\pi$.

18. Silica (Fused)

Data are reported for normal temperature over part of the wavelength range of interest. Data are also reported for several temperatures within the temperature range from normal temperature to 50 K below the melting point but only over the upper portion of the wavelength range of interest. Calculated normal incidence reflectance data are available at normal temperature [90014]. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Spectral Reflectance of Silica (Fused)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	0.80-2.60	27141	Fused quartz; clear; aluminum mirror reference standard; both θ and θ' were 45°.
298	1.90-29.0	30490	Vitreous silica; aluminum mirror reference standard; both θ and θ' were approx. 0°.
293	7.51-13.5	39543	Vitreous silica; both θ and θ' = 7°.
480	7.49-13.5	39543	Vitreous silica; both θ and θ' = 7°.
636	7.56-13.5	39543	Vitreous silica; both θ and θ' = 7°.
796	7.64-13.5	39543	Vitreous silica; both θ and θ' = 7°.
1035	7.67-13.5	39543	Vitreous silica; both θ and θ' = 7°.

Spectral Reflectance of Silica (Fused) (continued)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
1173	7.66-13.5	39543	Vitreous silica; both θ and θ' = 7°.
~298		90014	Normal incidence reflectance calculated from index of refraction data.

19. Silicon

Data are reported for normal temperature over almost all of the wavelength range of interest. Calculated normal incidence reflectance data for etched silicon are available at 300 K [90013]. The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Spectral Reflectance of Silicon

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	1.11-2.21	26044	Oxidized silicon; MgO used as reference material; both θ and θ' approx. 0°.
298	2.03-19.99	29605	n-type silicon doped with antimony ($N = 0.832 \times 10^{19}$ cm^{-3}); aluminum mirror used as reference standard; both θ and θ' approx. 0°.
298	2.00-14.03	32234	Phosphorus-doped ($N = 7.5 \times 10^{19}$ cm^{-3}); polished; both θ and θ' approx. 0°; five other curves presented for different annealing times (0.5 to 3.5 hrs) at 1310 K.

20. Silicon Carbide

For silicon carbide in bulk form, data are available at normal temperature over the entire wavelength range of interest, i.e., 1-12 μm. For silicon carbide in coating form, data are available at normal temperature but only over the lower portion of the wavelength range of interest. The temperature and wavelength ranges of the available data together with the data source references are given in the following two tables.

Spectral Reflectance of Silicon Carbide - Coating Form

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	0.30-2.60	6979	Silicon carbide from Norton Co.; on graphite substrate; measured relative to magnesium carbonate; reported error ±4%; θ = 9° and ω' = 2π.

Spectral Reflectance of Silicon Carbide - Bulk Form

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
~298	1.0-15.0	37398	98.1 pure powder, mesh size 320; three curves for compaction pressures of 1,400, 7,000, and 28,000 psi given; θ = approx. 0° and ω' = 2π.
~298	1.0-15.0	37398	98.1 pure powder; compacted at 42,000 psi; three curves presented for particle sizes 7, 30, and 70 μm; θ = approx. 0° and ω' = 2π.
~298	0.23-2.65	35840	98% pure; black powder; compacted at 70,500 psi; MgO reference standard; θ = 0° and ω' = 2π; two other curves presented for compaction pressures of 11,750 and 35,250 psi.

21. Silicon Nitride

For silicon nitride in bulk form, data are available at normal temperature but only over the lower portion of the wavelength range of interest. The temperature and wavelength ranges of the available data together with the data source references are given in the following table. No data are available for silicon nitride in coating form.

Spectral Reflectance of Silicon Nitride - Bulk Form

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	0.23-2.65	34908	>99% pure; compacted powder, compaction pressure 2350 psi; MgO used as reference standard; θ = approx. 0° and ω' = 2π; three other curves given for compaction pressures of 11,800, 35,300, and 70,500 psi.
~298	0.23-2.65	35840	Powder; compaction pressure 70,500 psi; MgO used as reference standard; θ = 0° and ω' = 2π; three other curves given for compaction pressures of 2,350, 11,750, and 35,250 psi.
298	0.23-2.65	22272	Sintered at 1673 K for 2 hrs; density 1.82 g cm^{-3}, theoretical density 3.44 g cm^{-3}; x-ray structure α-Si_3N_4 + β-Si_3N_4; MgO used as reference standard; θ = approx. 0° and ω' = 2π.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Reflectance*

Material	Normal Temperature	Normal Temp. to 50° below M.P.	50° below M.P. to M.P.	M.P. to 20° above
1. Al Alloy 2024	V^-, M^+	M^+	M	M
2. Al Alloy 7075	V^-, M^+	M^+	M	M
3. Ti Alloy 6Al-4V	D^-	M^+	M	M
4. Hadfield Manganese Steel	M^+	M^+	M	M
5. Boron fiber aluminum metal matrix composite	M^+	M	N	N
6. Boron fiber epoxy composite	M^+	M	N	N
7. Graphite fiber aluminum metal matrix composite	M^+	M	N	N
8. Graphite fiber epoxy composite	M^+	M	N	N
9. Acrylic resins	M^+	M^+	M	M
10. Lucite	D^-	M^+	M	M
11. Polycarbonate plastics	M^+	M^+	M	M
12. Silicone resins	M^+	M^+	M	M
13. Aluminum oxide (Wesgo Al-300)	M^+	M	M	N
14. Boron nitride	D^-	N	N	N
15. Calcium aluminum silicate (Corning 9753)	M^+	M	M	N
16. Magnesium fluoride (Kodak IRTRAN 1)	D^-	M	M	N
17. Pyroceram (Corning 9606)	M^+	M	M	N
18. Silica (fused)	D^-	D^-	M	N
19. Silicon	D^-	M	M	N
20. Silicon carbide	D^-	M	N	N
21. Silicon nitride	D^-	M	N	N

* See the explanation of codes on page 4.

E. Absorptance

1. Aluminum Alloy 2024

Experimental data on the radiative absorptance of Aluminum Alloy 2024 are practically not available. However, absorptance at normal temperature can be computed from the reflectance and emittance data. No information on absorptance is available for temperature other than normal.

There are plenty of experimental data on the solar absorptance produced by the research activities on the thermal control surfaces in the outer space environment. These data are highly dependent on the surface conditions and sample treatment. As a result, these data are useful only for very specific problems.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Aluminum Alloy 2024

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
323	0.25-27.0	29202	Only emittance and reflectance are presented but absorptance can be calculated therefrom.
		6596	Solar absorptance of Al Alloy 2024 samples "as received", "clean and smooth", and "polished"; measured at various temperatures.
		28845	Solar absorptance of Al Alloy 2024-T3 samples with various treatments; computed from reflectance data between 0.26 and 2.6 μm.
		31646	Normal solar absorptance of Al Alloy 2024 samples "as received" and "machine polished and degreased".
300		40746	Solar absorptance can be computed from reflectance data between 0.4 and 25.0 μm.
295-340		52095	Normal solar absorptance reported as a constant in the temperature range measured.

2. Aluminum Alloy 7075

Experimental data on the radiative absorptance is practically not available. However, absorptance at normal temperature range can be computed from reflectance and emittance data. No information is available for the absorptance at temperature other than normal.

There are a number of experimental data on the solar absorptance resulted from research activities on the thermal control surfaces in the outer space environment. These data are highly dependent on the surface conditions and sample treatment. As a result, these data are useful only for very specific problems.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Aluminum Alloy 7075

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
323	0.25-27.0	29202	Only emittance and reflectance are presented but absorptance can be calculated from these data.
		6596	Solar absorptivity of Al Alloy 7075 samples "as received", "clean and smooth", and "polished"; measured at various temperatures.
298-358		52095	Normal solar absorptance reported as a constant in the temperature range measured.
300		43493	Solar absorptance of Al Alloy 7075-T6 anodized to various thickness.

3. Titanium Alloy 6Al-4V

Experimental data on the radiative absorptance is not available. However, with the aid of the reflectance and emittance data, absorptance at normal temperature can be computed.

There exists a few experimental data on the solar absorptance resulted from NASA research on the thermal control surfaces in the outer space conditions. These data are highly dependent on the surface conditions and sample treatment and are useful only for very specific problems.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Titanium Alloy 6Al-4V

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
~ 300		24746	Solar absorptance of a sample as received.
373	0.3-3.0	35744	Solar absorptance of a sample under proton bombardment at various proton densities.
700, 925, 1150		68308	Solar absorptance computed from reflectance data between 1.5 and 15 μm.

4. Hadfield Manganese Steel

No information on radiative absorptance is available.

5. Boron Fiber Aluminum Metal Matrix Composite

No information is available.

6. Boron Fiber Epoxy Composite

No information is available.

7. Graphite Fiber Aluminum Metal Matrix Composite

No information is available.

8. Graphite Fiber Epoxy Composite

No information is available.

9. Acrylic Resins

No information is available for other kinds of acrylic resin except Lucite, for which see the next subsection.

10. Lucite

Experimental data on the radiative absorptance are practically not available. However, absorptance at normal temperature can be computed from the reflectance and transmittance data. Only one set of data on absorptance is found and is listed in the following table.

Normal Spectral Absorptance of Lucite

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	0.27-2.70	32388	Normal spectral absorptance of Lucite of 1/8" thick.

11. Polycarbonate Plastics

No information is available.

12. Silicone Resins

Experimental data on the radiative absorptance is not available. However, with the aid of reflectance and transmittance data, the absorptance at normal temperature can be calculated.

There exists a number of solar absorptance data. These data are made available by the space research activities. Use of the data is limited to very specific problems.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Silicone Resins

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
295		31253	Solar absorptance of coatings of silicone resin with additive Pb, S on Al substrate; computed from reflectance data between 0.2 μm and 15 μm.
300		41421	Solar absorptance of silicone resin 391-15-170 coatings on Al substrate under various levels of UV and X-ray exposures.
300		41919	Near normal solar absorptance of methyl silicone, Owens - Illinois type 650.

13. Aluminum Oxide (Wesgo Al-300)

Experimental data on the radiative absorptance of aluminum oxide at temperatures far below the melting point are available, which, however, are not for Wesgo Al-300.

There are plenty of experimental data on the solar absorptance produced by the research activities on the thermal control surfaces in the outer space environment. The use of these data is limited to very specific problems.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Aluminum Oxide

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	6.25-9.09	38694	Spectral absorptance of single crystal of α-Al_2O_3.
298	2.5-6.67	43875	Spectral absorptance of three ruby samples: (1) flux ruby, (2) hydrothermal ruby with impurity Cr, and (3) hydrothermal ruby with impurity Li.

Absorptance of Aluminum Oxide (continued)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	2.0-12.0	56876	Spectral absorptance of aluminum oxide particles of 6.28 μm or 12.2 μm in diameter suspended in CCl_4 or CS_2.
300	4.2-8.0	27083	Spectral absorptance of α-Al_2O_3 samples of various thickness.
298		10060	Near normal solar absorptance computed from spectral reflectance data between 0.3 and 3 μm for above atmosphere conditions and also for sea level conditions.
156, 278, 400		35545	Solar absorptance of evaporated saphire on Al substrate.
880		38992	Al_2O_3 coating; normal spectral emittance measured; solar absorptance calculated.
298	0.27-1.80	47275	Evaporated sapphire onto a pure silver coating on an Al substrate; normal spectral absorptance measured; normal solar absorptance also measured.
		53115	Solar absorptance of thin film Al_2O_3 coating measured in a simulated space environment.
		25215	Hemispherical solar absorptance of plasma-sprayed Al_2O_3 coatings before and after nuclear irradiation.
298	0.3-3.0	10060	Normal solar absorptance of Rokide A coating on stainless steel 446 substrate; computed from spectral reflectance data for above atmosphere conditions and also for sea level conditions.
83-400		48258	Total solar absorption of Rokide A coating on Al substrate; computed from reflectance data.

14. Boron Nitride

Experimental data for radiative absorptance at normal temperature are available. At high temperatures only one set of data measured at 2223 K is found.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Boron Nitride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	7.0-14.0	27083	Absorption spectrum of cubic single crystal BN.
300	3.0-35.0	32929	Absorption coefficient of pyrolytic BN for both polarized rays.
298	2.5-25.0	42872	Cubic boron nitride; computed from reflectance data.
300	2.9-20	90009	Polycrystalline hexagonal BN oriented along c-axis; absorption coefficient computed from reflective spectrum.
293	5.0-22.5	90011	Absorption spectra for several samples of BN under shock compression.
300	4.0-35.0	90008	Absorption coefficient for vapor-deposited BN film; polycrystalline, hexagonal, highly oriented; measured for incident light normal to c-axis and also for parallel to c-axis.
300	2.0-26.0	90010	Absorption coefficient of vapour-deposited BN of 1 mil thick.
2223	1.0-15.0	90007	Absorption coefficient of a boron nitride film deposited on a tungsten substrate.

15. Calcium Aluminum Silicate (Corning 9753)

No information is available.

16. Magnesium Fluoride (Kodak IRTRAN 1)

Experimental data on the radiative absorptance are very limited. However, absorptance at normal temperature can be computed from the reflectance and emittance data. No information is available for the absorptance at temperatures other than normal.

There are experimental data on the solar absorptance produced by the research activities on the space exploration. These data are highly dependent on the surface conditions and sample preparation. Therefore, these data are used only for very specific problems.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Magnesium Fluoride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
333, 393, 453	3.0-15.0	45698	Normal spectral absorptance of Kodak Irtran 1, hot pressed; measured in vacuum.
		35545	Solar absorptance of multilayer coating surface of $MgF_2/Fe_2O_3/Al$; measured on OVI-10 satellite.
		35819	Solar absorptance of alternate coatings of MgF_2-Mo or MgF_2-CeO systems on Mo substrate at various temperatures.
533, 811		36683	Solar absorptance of multilayer system coatings of MgF_2-Mo-CeO, MgF_2-Mo and MgF_2-CeO-Mo on Mo substrate.
		43423	Solar absorptance of the multilayer system of Al-FeO_x (3/4 λ) -MgF_2 on Al or Au substrates.

17. Pyroceram (Corning 9606)

No information is available.

18. Silica (Fused)

Experimental data on the radiative absorptance for various forms of silicon dioxide at normal temperature are available. No information is available at temperatures other than normal. Solar absorptance data on some highly specified SiO_2 coatings are also available.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Silicon Dioxide

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
293	7.6-25.0	37023	Normal absorption spectra of four SiO_2 samples, namely α-quartz, α-cristobalite, fused silica, and thermal oxide; the resonance wavelengths are also presented.
300	2.5-25.0	56079	Normal spectral absorption of SiO_2 films on crystalline quartz substrates.
		43484	Solar absorptance of surfaces of silica coating on various substrates; measured in a simulated space environment.

Absorptance of Silicon Dioxide (continued)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
294, 533		47275	Solar absorptance of surfaces of silica coating on various substrate and subjected to UV radiation and thermal cycling.
293	9.0	68201	Absorptances of silica coatings on silicon substrate.

19. Silicon

Experimental data on the radiative absorptance of pure silicon is practically not available. However, absorptance at normal temperature can be computed from the reflectance data.

Absorptance data for some specially treated samples are found in the literature and are listed in the following table.

Absorptance of Silicon

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	1.2-2.7	37021	High-resistivity single crystal; induced absorption produced by 1.06 μm laser light.
80	2.0-4.0 4.5-14.5 17.0-25.0	69682	n- and p-type; irradiated with large neutron doses and annealed at various temperatures.
300	0.73-2.1	68557	Spectral absorptance of silicon film deposited on a quartz or glass substrate.
		23610	Solar absorptance of a boron-doped silicon film on a nickel plate.

20. Silicon Carbide

Experimental data on the radiative absorptance are available only in the temperature range far below the melting point. Data for solar absorptance are also available.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Absorptance of Silicon Carbide

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
293-1773	1.0-4.0	29591	Absorption of α-sic crystal.
300	1.0-10.0	32821	Absorption coefficient of α-II sic; determined from transmission data.
300	0.39-25.0	32121	Absorption of boron-doped sic crystals; computed from reflection and transmission data.
298	0.4-2.6	32388	Normal spectral absorptance of Globar.
300	0.375-8.0	64205	Absorption coefficient of hexagonal sic.
100, 300	5.0-10.0	70890	Spectral absorption of α-sic (6H) activated by UV illumination.
298		10060	Near normal solar absorptance of sic for above atmosphere conditions and also for sea-level conditions.

21. Silicon Nitride

Very limited experimental works have been done on silicon nitride. Only one paper on radiative absorptance is found and the pertinent information is extracted as follows.

Absorptance of Silicon Nitride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	2.5-4.0	44942	Absorptance of commercial Si_3N_4 powder.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Absorptance*

Material	Normal Temperature	Normal Temp. to 50° below M. P.	50° below M. P. to M. P.	M. P. to 20° above
1. Al Alloy 2024	V^-	V^a	V^a	V^a
2. Al Alloy 7075	V^-	V^a	V^a	V^a
3. Ti Alloy 6Al-4V	V^-	V^a	V^a	V^a
4. Hadfield Manganese Steel	V^a	V^a	V^a	V^a
5. Boron fiber aluminum metal matrix composite	V^a	V^a	V^a	V^a
6. Boron fiber epoxy composite	V^a	V^a	V^a	V^a
7. Graphite fiber aluminum metal matrix composite	V^a	V^a	V^a	V^a
8. Graphite fiber epoxy composite	V^a	V^a	V^a	V^a
9. Acrylic resins	V^b	V^b	V^b	V^b
10. Lucite	V^-	V^b	V^b	V^b
11. Polycarbonate plastics	V^b	V^b	V^b	V^b
12. Silicone resins	V^-	V^b	V^b	V^b
13. Aluminum oxide (Wesgo Al-300)	D^-	V_b	V_b	V_b
14. Boron nitride	D^-	V_b	V_b	V_b
15. Calcium aluminum silicate (Corning 9753)	V_b	V_b	V_b	V_b
16. Magnesium fluoride (Kodak IRTRAN 1)	V^-	V^b	V^b	V^b
17. Pyroceram (Corning 9606)	V^b	V^b	V^b	V^b
18. Silica (fused)	D^-	V^b	V^b	V^b
19. Silicon	D^-	V^b	V^b	V^b
20. Silicon carbide	D	V^b	V^b	V^b
21. Silicon nitride	V^-	V^b	V^b	V^b

* See the explanation of codes on page 4 except for the following additional codes:

V^a - No data are available but estimated values may be derived from appropriate data on emittance or reflectance.

V^b - No data are available but estimated values may be derived from appropriate data on emittance or reflectance and transmittance.

F. Transmittance

1. Aluminum Alloy 2024

This material is sufficiently opaque that transmittance need not be considered.

2. Aluminum Alloy 7075

This material is sufficiently opaque that transmittance need not be considered.

3. Titanium Alloy 6Al-4V

This material is sufficiently opaque that transmittance need not be considered.

4. Hadfield Manganese Steel

This material is sufficiently opaque that transmittance need not be considered.

5. Boron Fiber Aluminum Metal Matrix Composite

This material is sufficiently opaque that transmittance need not be considered.

6. Boron Fiber Epoxy Composite

This material is sufficiently opaque that transmittance need not be considered.

7. Graphite Fiber Aluminum Metal Matrix Composite

This material is sufficiently opaque that transmittance need not be considered.

8. Graphite Fiber Epoxy Composite

This material is sufficiently opaque that transmittance need not be considered.

9. Acrylic Resins

The softening point of acrylic resins generally falls in the range 250-400 K. There are no data available for acrylic resins above normal temperature. Limited data are available at room temperature for "Lucite" (DuPont) and "Plexiglass" (Rohmand Haas), which are proprietary formulations of poly(methyl methacrylate), one kind of acrylic resin. DuPont produces special formulations of "Lucite" which have various transmission properties for different wavelength ranges, so more complete specification of the formulations of interest may be necessary. Single data point

for several acrylic resins other than poly(methyl methacrylate) is available at room temperature. Most of these acrylics have been considered as candidates for optical material in aerospace reconnaissance.

The temperature and wavelength ranges of the available data for other acrylic resins than Lucite together with the data source references are given in the following table.

Transmittance of Acrylic Resins Other Than Lucite

Material	Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
Poly(cyclohexyl methacrylate)	300	0.3-2.2	40338	6.75 mm thick sample.
Poly(isobutyl methacrylate)	300	0.3-2.2	40338	6.67 mm before and after fading.
Poly(allyl methacrylate)	300	0.3-2.2	40338	7.13 mm before and after fading.
Poly(n-butyl methacrylate)	300	2.0-15.0	19814	
Poly(acrylic acid)	300	3-7	34840	
Poly(ethylene glycol dimethacrylate)	300	0.3-2.2	40338	6.85 mm thick.

10. Lucite

Lucite is one kind of acrylic resin and is the trade name of DuPont for poly(methyl methacrylate).

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Lucite

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	3.3-20	40581	"Plexiglas"; 5, 7 μ films.
300	3.3-20	40581	Obtained as powder from DuPont; 2, 25 μ films.
300	2.0-15.0	24947	"Lucite"; 0.010 in. thick.
300	2.0-15.0	19814	Thicknesses unknown.
300	0.2-2.2	40338	7.46 mm before and after fading.

Transmittance of Lucite (continued)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	0.2-2.6	47094	1/4 in. acrylic sheet; before and after simulated solar irradiation.
300	0.2-2.6	47094	Cross linked methacrylate 1/4 in. thick; before and after simulated solar irradiation.
300	2.0-15.0	51594	

11. Polycarbonate Plastics

Available transmittance data for these plastics are limited to the 1-2.6 μm range. Partial data are available for "Merlon" (softening point 410 K) and "Lexan" polycarbonates (softening point 428 K), both of which have found applications in missile construction. Partial data is also available for poly(allyl diglycol carbonate) "CR-39" which has been considered for use as a light-weight optical material for aerospace reconnaissance. No high temperature data are available.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Polycarbonate Plastics

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	0.2-2.5	29424	"Merlon"; 5 mil thickness.
300	0.3-2.5	57891	"Merlon"; unannealed; 9.5 mm thick.
300	0.8-2.6	57891	"Lexan"; thickness 4.27 mm.
300	0.3-2.2	40338	"Polycarbonate"; 6.15 mm thick; before and after fading.
300	0.3-2.2	40338	Poly(allyl diglycol carbonate) "CR-39"; 7.2 mm thick; before and after fading.

12. Silicone Resins

Partial room-temperature data are available for several silicone resins which have been considered for application in aerospace construction. Poly(dimethylsilanediol) with melting point 740 K has been considered for use as a matrix material for flexible windows and domes in manned spacecraft, although it has been suggested that it has insufficient tear resistance for this purpose. Polyphenyl silicone has been considered for use as a paint-like organic coating for spacecraft designed to control emission and

absorption of radiant energy. Silicone DC 808 has been considered for similar uses. Silicone XR6-2044 has been considered for use as a coating for solar cells. Owens Illinois "Glass Resin 100" has been studied for possible use as a light-weight optical material for aerospace reconnaissance. No high temperature transmittance data are available for any of these silicone resins and wavelength ranges are limited.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Silicone Resins

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	2.0-15.0	51594	Unspecified silicone resin.
300	2.7-5.5	51318	Carboxyorganosilica powder
300	0.2-10	61459	Polydimethylsilanediol
300	1-15	24833	Polyphenyl silicone; before and after U-V irradiation.
300	6-14	35546	Silicone DC 808.
300	0.2-2.2	40338	Owens-Illinois "Glass Resin-100"; 6.67 mm thick sample.
300	0.3-2.1	19818	Silicone XR6-2044 (Dow Corning); 0.046 in. thick.

13. Aluminum Oxide (Wesgo Al-300)

There are no available data for the transmittance of Wesgo Al-300. Limited data are available for commercial alumina formulations which may be similar in nature to Wesgo Al-300. Sources for these data are shown in the accompanying table. However, it is probable that measurements will be necessary in order to obtain reliable recommendations for the transmittance of Wesgo Al-300 itself.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Aluminum Oxide

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	1,2,4,5,8	29570	Coors' AD-94,96,99,85 (numbers indicate percentage alumina); McDaniel's AP35 (99% Al_2O_3), cast; McDaniel's AP35 (99% Al_2O_3), isostatic; 0.005 in. and 0.010 in. thick samples.
295	2-7.5	20771	American Lava Co.; ceramic; 96% Al_2O_3.

14. Boron Nitride

Room temperature data are available for single crystal boron nitride and for commercially obtained, analytical reagent grade samples which were ground to a fine powder to minimize scattering and examined as Nujol mulls. No high temperature data is available.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Boron Nitride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	2-16	60470	Hexagonal.
313	1-50	40525	6 mm thick; ground and polished to 5 fringes or better; 30° angle incidence.
300	2-16	58818	Fine powder; Nujol mull.
300	2.7-23	42872	Single crystal platlets with cubic structure (30 μm thick); grown at very high temperature and pressure; 10^{10} Ω-cm electrical resistivity.
300	2.7-24	42872	Single crystal platlets with cubic structure (30 μm thick); beryllium doped; grown at very high temperature and pressure; 10^4 Ω-cm electrical resistivity.

15. Calcium Aluminum Silicate (Corning 9753)

There are no available data for the transmittance of Corning 9753. Limited data are available for glasses of similar composition which may be similar in nature to Corning 9753. However, it is probable that measurements will be necessary in order to obtain reliable recommendations for the transmittance of Corning 9753 itself.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Calcium Aluminum Silicate

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	2-5.5	39835	Glass C-1458; 6.8 wt.% SiO_2, 41.0% Al_2O_3, 52.0% CaO.
300	2-5.5	39835	Glass C-1474; 6.8 wt.% SiO_2, 43.7% Al_2O_3, 49.5% CaO.

16. Magnesium Fluoride (Kodak IRTRAN 1)

IRTRAN 1 is a hot pressed, sintered compact of predominantly magnesium fluoride. The manufacturing details are still proprietary. Measurements of the transmittance of IRTRAN 1 at room temperature have been relatively extensive. Limited data are also available at temperatures up to 1073 K, and it should be possible to produce reliable estimates of transmittance in this range.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Magnesium Fluoride

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298-673	2-12	38674	IRTRAN 1; 2.8 mm thick; data at 100 K intervals.
300	1-15	38121	IRTRAN 1; 1.02 mm thick.
300	1-10	35848	IRTRAN 1; 1.02 mm thick.
300	0.2-15	36646	IRTRAN 1 and single crystal MgF_2; 0.110 in. thick.
300	0.2-3.0	44164	IRTRAN 1; 2 mm thick; ±2% uncertainty claimed.
300	2-10	30100	IRTRAN 1; ground and polished to 7 fringes.
298-673	2-12	20810	IRTRAN 1; data at 100 K intervals.
299, 673, 873, 1073	1-10	17017	IRTRAN 1; 1.75 mm thick.
300	1-10	25656	Hot pressed powdered MgF_2 gives polycrystalline compact; 0.2 mm thick.
300	1-10	10703	Hot pressed MgF_2; 2.24 mm thick.
300	5-50	51558	Single crystal MgF_2.
300	5-50	51558	99.98% pure powder; 2.0 mg in 400 mg CsI pellet.
300	0.14-6.0	49630	Single Rochon prism of dimensions 12 x 12 x 50 mm.

17. Pyroceram (Corning 9606)

Room-temperature data in the 1-8 μm wavelength range are available. Limited data are also available up to 1200 K for Corning 9606. Since it appears that the transmittance of pyroceramic materials shows very little temperature dependence, it should be possible to generate reliable estimates in this temperature range.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Pyroceram (Corning 9606)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298,770,900, 1040	1-5	29570	Corning 9606; single crystal of 0.125 x 0.5 x 1.5 in.; ± 5% precision claimed.
300	1,2,4,5,8	29570	Corning 9606; diffuse transmission; thickness 0.005 and 0.010 in.; ± 5% precision cross-section: 0.25 x 0.62 in.
295,1273	2-7.5	20771	Pyroceram, Corning.
293-1173	0.5-3.2	31344	Pyroceramic material; shows very little temperature dependence.

18. Silica (Fused)

Studies have been made [10703] of the potential usefulness of fused silica as an infrared dome material for missiles. It is excellent for use in the short wavelength range and is the best material for that range according to Ref. 10703. However, it cannot be used in the 3-5 μm range. In this region, such a dome suffers an appreciable transmission loss when temperature increases to 500 C from normal ambient temperature. Several manufacturers produce commercial formulations of silica glass developed especially for use in the ultraviolet or infrared ranges. The transmittance of these silicas will differ significantly according to the wavelength range. Room-temperature and high-temperature data are available for several of the commercial silica glasses.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Silica (Fused)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298-673	2.0-6.0	38674	GE type 106 (2.8 mm thick); polished within 5 green mercury fringes and parallelism tolerance of ± 2.5 μm; 100 K intervals.
298	0.8-2.6	27141	Clear fused quartz; about 1.6 mm thick.
300	3.7-20	38719	Cut and ground but not polished; 22 ± 2 x 10^{-3} mm thick.

Transmittance of Silica (Fused) (continued)

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	1-30	30490	Vitreous silica; 6500 Å thick.
298	1.0-4.6	35036	3.18 mm thick.
300	2.8-4.8		Good optical quality; 5.970 and 1.484 mm thick.
300	0.2-3.4	66747	Dynasil-1000, Suprasil W, Infrasil II, Corning 7940.
298, 1023, 1273, 1523, 1773	0.22-3.5	63687	GE type 151, GE type 105, Corning Vycor 7905; 0.953 cm thick samples.
300	2.0-15.0	59584	Vitreous silica.
300	0.8-4.6	47956	Vycor glass No. 790; 2 mm thick sample.
300	1-4.7	40764	Fused quartz; essentially opaque for $\lambda > 4.6\ \mu$.
300	1-4.7	40665	Suprasil, Ultrasil, Vitreosil.
300	0.2-2.8	37896	Homosil (0.625 in.), GE 104 (0.935 in.), Vycor 1913 (0.25 in.).
298-773	2-6	10703	Fused quartz glass; 2.85 mm thick sample.
300	6-14	33878	Corning 7940; 10 μ thickness of a blown film.
295, 923, 1073	0.15-4.0	35404	Corning 7940 (30 mm, 1 mm); Amersil (30 mm, 1 mm); Spectrosil (30 mm, 1 mm); optically polished; parallel.

19. Silicon

Silicon is a brittle material below 1273 K but above this temperature it can be caused to undergo substantial plastic deformation. Silicon has been studied for use as infrared dome material for small air to air missiles [10703]. For this purpose it can be used in the 1-12 μm range up to 523 K and over the 6-7 μm range to a temperature of 593 K. Above this temperature it becomes increasingly opaque. Extremely small amounts of impurities greatly curtail its transmittance. For dome construction, the most feasible fabrication method appears to be a form of shell casting [48097]. Data for both single crystal and cast silicon is available at room temperature. Investigations of vapor deposition techniques for making domes have also been carried out [48097]. The transmittance of vapor deposited silicon and grown silicon differ greatly. High temperature data are available for single crystal silicon only.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Silicon

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
298	2-15	27345	6 ppb boron and 20 ppb phosphorus; polished to within 5 green mercury fringes.
298-673	1.14-11.98	20810	n-type silicon; 6 ppb boron and 20 ppb phosphorus; single crystal; polished; electrical resistivity 5 Ω-cm; data at 100 K intervals.
300	2-50	30100	Specimen 1 cm thick.
300	6-37	44931	Thickness 1.0 mm; conductivity 0.0086 Ω^{-1} cm^{-1}.
300	1-7	49418	Polished, undoped, carrier concentration 10^{16} cm^{-3}.
300	1-7	49418	Standard silicon photocell; polished.
300	6-15	44710	Wafer; mechanically polished to mirror finish.
300	0.84-15	46843	High purity; float zone refined; 1.5 mm thick.
298-673	1.2-12	38674	n-type silicon; polished to within 5 mercury fringes and a parallelism tolerance of ±2.5 μm; about 6 ppb boron and 20 ppb *phosphorus*; 5 Ω-cm; data at 100 K intervals.
300	5-35	36371	Highly pure silicon in 1, 5, 11 mm thicknesses.
300	1-10	56727	2 mm thick single crystal of unknown purity.
298	1-14	44850	n-type Si; undeformed, annealed.
300	1-12	40270	Pure, high resistivity silicon; 0.518 cm thick.
298, 573, 623, 673	1-10	10703	4.16 mm thick; single crystal.
298	1-15	48097	Cast silicon; 0.183 in. thick, 33 Ω-cm p-type.
298	1-15	48097	Vapor deposited silicon dome and grown silicon.
300	2.5-50	64446	10 mil thick plane parallel slice of 3 Ω-cm silicon.

20. Silicon carbide

An EPIC publication [34058] has reported data available in the literature as of 1965. Data for pure argon grown, single crystal alpha silicon carbide are available

for room temperature conditions. Data for single crystal n-type and p-type alpha silicon carbide with various concentrations of nitrogen and aluminum dopants are available at room temperature also. The only high-temperature data are for single crystal n-type alpha silicon carbide. The transmittance of silicon carbide varies greatly with crystalline structure and with type and amount of doping. It is seldom produced in a pure state.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Silicon Carbide

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	4-10	32821	Polycrystalline cubic SiC.
300	2-16	60470	Hexagonal.
300	0.35-10	34058	Pure argon grown, single crystal n-type α-SiC.
300	0.3-10	34058	Pure argon grown, single crystal p-type α-SiC; increasing amounts of aluminum dopant.
300	1-12	34058	Light green, nitrogen doped, single crystal, n-type α-SiC (6H); 0.007 mm thick.
300	1-12	34058	Clear, nitrogen doped, single crystal, n-type α-SiC (6H); 0.07 mm thick.
300	1-25	34058	Clear, single crystal, n-type, α-SiC (6H).
77, 293-1036	2.4-3.2	34058	Single crystal, n-type α-SiC.
300	0.4-1.5	65653	Boron doped, p-type crystals of α-SiC (6H); 400, 310, 480 μ thick samples; before and after neutron and α-particle irradiation.

21. Silicon Nitride

No data for bulk silicon nitride are available. Limited data for coatings of silicon nitride on Si, Ge, GaAs, and fused silica substrates are available for room temperature conditions. However, the techniques used in the deposition of the films are diverse and variable. Thus, while limited room-temperature data for specific samples are available, it may not be possible to recommend transmittance values for samples which are not similar to those for which data are available.

The temperature and wavelength ranges of the available data together with the data source references are given in the following table.

Transmittance of Silicon Nitride Coatings

Temperature Range (K)	Wavelength Range (μm)	Reference	Remarks
300	7-20	65344	Films formed on single crystal silicon surface.
300	1-16	45954	Films on GaAs substrate and Si substrates.
300	0.2-24	45177	Films deposited on fused silica blanks at 850 C.
300	2.5-25	70779	Film deposited on Si substrate.
300	3-15	52872	Film 1 μm thick deposited on Si at 1000 C.
300	7-12	48136	Film deposited on Si at 850 C.
300	0.9-2.6	61411	Films formed on Si, Ge, GaAs filters by r-f sputtering.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Transmittance*

Material	Normal Temperature	Normal Temp. to 50° below M.P.	50° below M.P. to M.P.	M.P. to 20° above
1. Al Alloy 2024	V^c	V^c	V^c	V^c
2. Al Alloy 7075	V^c	V^c	V^c	V^c
3. Ti Alloy 6Al-4V	V^c	V^c	V^c	V^c
4. Hadfield Manganese Steel	V^c	V^c	V^c	V^c
5. Boron fiber aluminum metal matrix composite	V^c	V^c	V^c	V^c
6. Boron fiber epoxy composite	V^c	V^c	V^c	V^c
7. Graphite fiber aluminum metal matrix composite	V^c	V^c	V^c	V^c
8. Graphite fiber epoxy composite	V^c	V^c	V^c	V^c
9. Acrylic resins	D^-	M^+	M	N
10. Lucite	M^+	M^+	M	N
11. Polycarbonate plastics	M^+	M^+	M	N
12. Silicone resins	D^-	M^+	M	N
13. Aluminum oxide (Wesgo Al-300)	M^+	M	N	N
14. Boron nitride	D	M	N	N
15. Calcium aluminum silicate (Corning 9753)	V^-	M	N	N
16. Magnesium fluoride (Kodak IRTRAN 1)	D	V	M	N
17. Pyroceram (Corning 9606)	D^-	D^-	N	N
18. Silica (fused)	D	V^-, M	M	N
19. Silicon	D	V^-	M	N
20. Silicon carbide	D	V^-	N	N
21. Silicon nitride	D^-	M	N	N

* See the explanation of codes on page 4 except for the following additional code:
V^c - Transmittance is unimportant to be considered since the material is sufficiently opaque.

G. Thermal Expansion

1. Aluminum Alloy 2024

Experimental data are available from low temperature up to near the melting point. Based on this information together with the knowledge of the solid density at room temperature it is generally possible to construct a smooth density curve from normal temperature to the melting point. An attempt could then be made to evaluate the liquid density above the melting point by means of the mixing rule [90016]: $\rho = \sum_i \rho_i x_i$, where ρ is the density of the alloy, ρ_i is the density of the i-th pure component and x_i is the mole fraction of the i-th pure component. In the liquid range, a linear dependence of the density on temperature is assumed. As a result, thermal expansion will have some uncertainty above the melting point.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Aluminum Alloy 2024

Temperature Range (K)	Reference	Remarks
83-773	6940	Experimental data.
116-699	9736	Experimental data.
106-516	37995	Experimental data.
293-673	35448	Experimental data (6 curves).
213-573	56783	Experimental data (3 curves).
78-777	63999	Experimental data.
293-393	68046	Experimental data.

2. Aluminum Alloy 7075

TPRC Report 16 [90015] contains values for the density for this alloy from room temperature to 600 K above the melting temperature. Experimental data on thermal linear expansion are also available up to the melting temperature. On the basis of this information, estimation of thermal expansion on this alloy from room temperature to 20 K above the melting temperature seems to be no problem.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Aluminum Alloy 7075

Temperature Range (K)	Reference	Remarks
0-2400	90015	Data on density.
0-300	50161	Experimental data.
116-699	9736	Experimental data.
18-573	46067	Experimental data.
213-573	56783	Experimental data (2 curves).
83-773	6940	Experimental data.
78-813	63999	Experimental data.

3. Titanium Alloy 6Al-4V

We can probably extrapolate the experimental data to the melting point. These values could then be checked using the density values for titanium alloy A-110AT in Ref. [90015] as a guide. The density values of alloy A-110AT could also be used as a first approximation for the thermal expansion of alloy 6Al-4V above the melting point. Also, the mixing rule: $\rho = \sum_i \rho_i x_i$ could be used to check these values above the melting point.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
4-922	31540	Experimental data.
310-922	31460	Experimental data (4 curves).
293-1699	43639	Experimental data (2 curves).
18-573	46067	Experimental data.
78-1366	63999	Experimental data.
293-393	68046	Experimental data.
293-773	52262	Experimental data.

4. Hadfield Manganese Steel

There is only one Russian paper which contains the thermal linear expansion for Hadfield Steel uncovered in the present literature survey. These available data may probably be extrapolated to the melting point.

The temperature range of the available data together with the data source reference is given in the following table.

Thermal Expansion of Hadfield Manganese Steel

Temperature Range (K)	Reference	Remarks
293-1173	49164	Experimental data.

5. Boron Fiber Alumimum Metal Matrix Composite

Little has been reported on the thermal expansion behavior of this composite. In Ref. [64585] authors indicated that the longitudinal thermal expansion for this composite can be predicted with certainty. But in predicting the directional thermal expansion at each temperature both longitudinal and transverse thermal expansion coefficients determined experimentally are needed.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Boron Fiber Aluminum Metal Matrix Composite

Temperature Range (K)	Reference	Remarks
293	34631	Experimental data.
293-773	69817	Experimental data.

6. Boron Fiber Epoxy Composite

Little has been reported on the thermal expansion behavior of this composite. In order to predict the directional thermal expansion, the information on thermal expansion coefficients for both longitudinal and transverse directions is needed (see the discussion in the subsection on graphite fiber epoxy composite). The only available data on this material is listed below.

Thermal Expansion of Boron Fiber Epoxy Composite

Temperature Range (K)	Reference	Remarks
293	34631	Experimental data.

7. Graphite Fiber Aluminum Metal Matrix Composite

No data are available from the literature. Using the same technique as that for other composites, we may be able to predict the directional thermal expansion if the required information on the longitudinal and transverse thermal expansion coefficients is available, which unfortunately is not.

8. Graphite Fiber Epoxy Composite

Little has been reported on the thermal expansion behavior of the composite [64585, 67521, 69817]. The thermal expansion behaviors of unidirectional, balanced angle-ply, and complex laminated graphite-epoxy composite are always different. The expansion coefficient of the unidirectional composites is determined as a function of fiber orientation and is found to follow the simple equation [60284]: $\alpha_\theta = \alpha_L \cos\theta^2 + \alpha_T \sin\theta^2$, where θ is angle between the direction of expansion coefficient and that of fiber, α_L is the thermal expansion coefficient in the longitudinal direction ($\theta = 0$), and α_T is called the transverse thermal expansion coefficient ($\theta = 90$). In an undirectional composite, the longitudinal coefficient (α_L) is almost identical with that of the graphite fiber, a fact supported by the experimental results. However, the transverse coefficient (α_T) is very sensitive to the exact configuration of the fibers in the matrix. Furthermore, its calculations involves the transverse properties of the fibers, which are not known at the present time with certainty. As a result, in predicting the directionality of thermal expansion of a unidirectional composite, the values for both the longitudinal and transverse thermal expansion coefficients are determined experimentally.

For the expansion coefficient of balanced, symmetric angle-ply panels in a direction bisecting the angle between plies, Halpin and Pagano's equations [90020] are adequate for predictions.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Graphite Feber Epoxy Composite

Temperature Range (K)	Reference	Remarks
293	34631	Experimental data.
293-433	60284	Experimental data.

9. Acrylic Resins

Included in this subsection are three major categories of acrylic resins: polymethacrylate, polyacrylate, and copolymer of acrylonitrile. The fourth category: poly(methyl methacrylate) will be discussed in the next subsection under the heading "Lucite".

There are many variations in these materials, mainly concerned with the combinations of mathacrylate esters and acrylate esters, as well as acrylonitrile used in making these polymers. Most experimental data on thermal expansion are available for polymethacrylates and little information is available for polyacrylates and copolymers of acrylonitrile. Generally speaking, among them copolymers of acrylonitrile have the higher softening point at about 350 K, and polymethacrylates have the intermediate softening point ranging from 273 K to 338 K, and polyacrylates have the lower softening point ranging from 248 K to 276 K. On the basis of this information, to obtain thermal expansion values below and above the softening point for some of the polymethacrylates seems to be of no problem, but for polyacrylates and copolymers of acrylomitrile seems to be of some uncertainty.

The temperature ranges of the available data together with the data source references for the three categories of acrylic resins are given in the following three tables.

Thermal Expansion of Polymethacrylate

Temperature Range (K)	Reference	Remarks
294-336	40338	Experimental data (8 curves).
93-373	47797	Experimental data (12 curves).
20-120	50783	Experimental data (9 curves).
10-190	68197	Experimental data (2 curves).
20-275	70351	Experimental data.

Thermal Expansion of Polyacrylate

Temperature Range (K)	Reference	Remarks
93-283	47797	Experimental data.

Thermal Expansion of Copolymer of Acrylonitrile

Temperature Range (K)	Reference	Remarks
293-403	44424	Experimental data.

10. Lucite

Experimental expansion data are available below and above the glass transition temperature. We will be able to generate recommended thermal expansion values with certainty.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Lucite

Temperature Range (K)	Reference	Remarks
83-373	38279	Experimental data.
297-378	40338	Experimental data (2 curves).
293-375	46371	Experimental data.
93-393	47797	Experimental data.
293-403	50783	Experimental data.
263-333	63727	Experimental data.
263-303	67504	Experimental data (3 curves).

11. Polycarbonate Plastics

Experimental data are available near the glass transition temperature, and will be able to generate thermal expansion values below this temperature. It seems not possible to predict thermal expansion for the liquid phase.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Polycarbonate Plastics

Temperature Range (K)	Reference	Remarks
293	38279	Experimental data.
295-328	40338	Experimental data.
293	46814	Experimental data.
293	49682	Experimental data.
293	50887	Experimental data.
293	90019	

12. Silicone Resins

Most of the available experimental data covers a wide range of temperature both below and above the glass transition temperature. On the basis of this information, to generate recommended thermal expansion values for some of the silicone resins seems to be of no problem.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Silicone Resins

Temperature Range (K)	Reference	Remarks
75-619	35530	Experimental data (4 curves).
90-423	37897	Experimental data (3 curves).
72-297	47141	Experimental data (2 curves).
0-340	55206	Experimental data.
76-297	53670	Experimental data.
298-423	46527	Experimental data.
73-473	44499	Experimental data (3 curves).
90-703	58327	Experimental data.
273-473	45231	Experimental data (3 curves).

13. Aluminum Oxide (Wesgo Al-300)

In reference [90017] the purity (97.6 Al_2O_3) and thermal expansion data for Wesgo Al-300 are given. TPRC Report 16 [90015] contains values for the density of pure aluminum oxide from room temperature to 300 K above the melting point. Experimental data on the thermal expansion of aluminum oxide with purity of 95% or higher are also available from room temperature to the melting point. As a result, thermal expansion values from room temperature to above the melting point will possibly be generated with certainty.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Aluminum Oxide

Temperature Range (K)	Reference	Remarks
298-1273	90017	97.6% Al_2O_3.
0-2600	90015	Data on density of pure Al_2O_3.

Thermal Expansion of Aluminum Oxide (continued)

Temperature Range (K)	Reference	Remarks
293-2300	90018	Recommended values for pure Al_2O_3.
293-873	52055	Experimental data for 95% Al_2O_3.
298-1273	52681	Experimental data for 96% Al_2O_3.
323-1273	53283	Experimental data for 95% Al_2O_3.
293-1973	52689	Experimental data for 95.5% Al_2O_3.
673-2067	46010	Experimental data for 98% Al_2O_3.

14. Boron Nitride

Experimental data are available up to 2273 K. Extrapolating the experimental data to the decomposition temperature (~2600 K) seems possible.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Boron Nitride

Temperature Range (K)	Reference	Remarks
293-1095	46081	Experimental data (2 curves).
273-1273	45040	Experimental data.
293-1073	18664	Experimental data.
298-1273	47961	Experimental data (2 curves).
283-1073	52676	Experimental data (2 curves).
293-2130	26008	Experimental data.
273-1348	47397	Experimental data (8 curves).
293-2273	66442	Experimental data.
273-1273	58910	Experimental data.
293-1023	57418	Experimental data (10 curves).

15. Calcium Aluminum Silicate (Corning 9753)

No data are available from the literature survey. Measurement using available technique and facility should be made.

16. Magnesium Fluoride (Kodak IRTRAN 1)

Since thermal expansion data for Irtran 1 are very close to that for ordinary magnesium fluoride for which recommended values are available [90018], we will be able to extrapolate the experimental data for Irtran 1 to the melting point.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Magnesium Fluoride

Temperature Range (K)	Reference	Remarks
293-m.p.	90018	Recommended data on magnesium fluoride.
273-333	39947	Irtran 1, experimental data.
70-310	53962	Irtran 1, experimental data (volumetric).
298-673	17017	Irtran 1, experimental data.
70-310	54713	Irtran 1, experimental data.

17. Pyroceram (Corning 9606)

Experimental data are available up to 1273 K. We will probably be able to extrapolate the experimental data to the softening temperature (1623 K) with some uncertainty. The predicted thermal expansion above the softening temperature will be more uncertain.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Pyroceram (Corning 9606)

Temperature Range (K)	Reference	Remarks
173-1273	25075	Experimental data.
298-673	57970	Experimental data.

18. Silica (Fused)

We will be able to extrapolate the experimental data to the melting point. Above the melting point the density data are available [90015]. Thus the thermal expansion data can be given below and above the melting point with little uncertainty.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Silica (Fused)

Temperature Range (K)	Reference	Remarks
1880-2600	90015	Data on density.
398-1173	46847	Experimental data.

Thermal Expansion of Silica (Fused) (continued)

Temperature Range (K)	Reference	Remarks
353-1000	52128	Experimental data.
54-723	51612	Experimental data (6 curves).
102-1273	43761	Experimental data (3 curves).
297-973	7036	Experimental data.
295-1475	52500	Experimental data (16 curves).
305-831	46298	Experimental data.
339-1265	55980	Experimental data.
293-1023	56075	Experimental data (2 curves).
293-1273	55940	Experimental data (35 curves).
268-328	48472	Experimental data (3 curves).
173-473	52896	Experimental data.
288-1338	55772	Experimental data (8 curves).

19. Silicon

The available experimental data covers the solid phase up to 1612 K. The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Silicon

Temperature Range (K)	Reference	Remarks
293-1073	47108	Experimental data.
273-1612	45165	Experimental data (3 curves).
300-8500	53476	Experimental data.
323-1123	52512	Experimental data (2 curves).
325-1073	45520	Experimental data.
303-1133	55976	Experimental data.
298-1405	52650	Experimental data (2 curves).
293-1018	57703	Experimental data (2 curves).
293-1186	55003	Experimental data.

20. Silicon Carbide

The available experimental data covers from room temperature up to 2700 K. Based on this information, we will be able to extrapolate the experimental data to the decomposition temperature (3260 K) with little uncertainty.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Silicon Carbide

Temperature Range (K)	Reference	Remarks
298-1773	46847	Experimental data (3 curves).
320-2023	35151	Experimental data.
293-1673	52801	Experimental data.
293-2273	50171	Experimental data.
293-2697	52140	Experimental data (2 curves).
373-1673	38757	Experimental data.

21. Silicon Nitride

Experimental data are available up to 2000 K for both α-Si_3N_4 and β-Si_3N_4. We will probably be able to extrapolate the experimental data to the sublimation temperature (2200 K). However, at temperatures above 1873 K, appreciable dissociation occurs, and therefore it is doubtful that we can predict the thermal linear expansion near the sublimation temperature with any certainty.

The temperature ranges of the available data together with the data source references are given in the following table.

Thermal Expansion of Silicon Nitride

Temperature Range (K)	Reference	Remarks
1073-1273	39522	Experimental data.
273-1273	45040	Experimental data.
521-1763	50954	Experimental data (5 curves).
294-2078	26074	Experimental data (6 curves).
293-1105	55003	Experimental data.
293-1715	54539	Experimental data (8 curves).
293-1104	53504	Experimental data.
273-1673	53238	Experimental data (6 curves).
273-1273	58280	Experimental data.
373-1973	38757	Experimental data.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Thermal Expansion*

Material	Normal Temperature	Normal Temp. to 50° below M.P.	50° below M.P. to M.P.	M.P. to 20° above
1. Al Alloy 2024	D	D	D	V⁻
2. Al Alloy 7075	D	D	D	D
3. Ti Alloy 6Al-4V	D	D	V	V
4. Hadfield Manganese Steel	D⁻	D⁻	M	M
5. Boron fiber aluminum metal matrix composite	D⁻	V⁻	M	M
6. Boron fiber epoxy composite	D⁻	V⁻	M	M
7. Graphite fiber aluminum metal matrix composite	M	M	M	M
8. Graphite fiber epoxy composite	D⁻	V⁻	M	M
9. Acrylic resins**	D⁻	D⁻	M	M
10. Lucite	D⁻	D⁻	D⁻	M
11. Polycarbonate plastics**	D⁻	V⁻	M	M
12. Silicone resins**	D⁻	D⁻	M	M
13. Aluminum oxide (Wesgo Al-300)	D	D⁻	V	V
14. Boron nitride	D	D	V⁻	N
15. Calcium aluminum silicate (Corning 9753)	M	M	M	M
16. Magnesium fluoride (Kodak IRTRAN 1)	D	D⁻	V⁻	M
17. Pyroceram (Corning 9606)	D	D⁻	V⁻	M
18. Silica (fused)	D	D	D⁻	D⁻
19. Silicon	D	D	V	N
20. Silicon carbide	D	D⁻	V	N
21. Silicon nitride	D	D	V⁻	N

* See the explanation of codes on page 4.

** The available data are for some specific materials only.

H. Specific Heat

1. Aluminum Alloy 2024

The temperature ranges of the available data together with the data source references are given in the following table. C_p values can be extrapolated to the melting point and C_p values for the molten alloy may possibly be estimated using empirical relation and/or the Kopp-Neumann rule with large uncertainty.

Specific Heat of Aluminum Alloy 2024

Temperature Range (K)	Reference	Remarks
73-723	6565	Alcoa sample 24S-T4.
373-773	8234	Data for various heat treated alloys.
273-573	9736	Alcoa sample; also reports values calculated from $C = 3R/A\ (1 + \beta T)$; agreement fairly good.
273-573	10106	Data for 24S-T4 and 24S annealed sample.
	34753	Review article; M. P. = 775 K.
173-473	36606, 47270	Values calculated from spectral properties of its surface and irradiance of the energy.
293-750	40327	Data for 2024-T3 and 2024-T4 samples.

2. Aluminum Alloy 7075

The temperature ranges of the available data together with the data source references are given in the following table. C_p values can be estrapolated to the melting point and C_p values for the molten alloy may possibly be estimated using empirical relation and/or the Kopp-Neumann rule with large uncertainty.

Specific Heat of Aluminum Alloy 7075

Temperature Range (K)	Reference	Remarks
73-723	6565	Alcoa sample.
273-573	9736	Also reports values from $C = 3R/A\ (1 + \beta T)$; agreement good.
273-573	10106	Applies model $C = 3nR/M$; agreement poor.
311-644	16987	Compilation.
273-573	23608	Compilation; 7075-T6 and annealed sample.
50-750	23881	

Specific Heat of Aluminum Alloy 7075 (continued)

Temperature Range (K)	Reference	Remarks
	34753	Review article; M.P. = 750 K.
1-800	90015	M.P. = 750-911 K; also reports density from 0-2400 K.

3. Titanium Alloy 6Al-4V

The temperature ranges of the available data together with the data source references are given in the following table. No data are available in the vicinity of the melting point. C_p values in that range may possibly be estimated using empirical relation and/or the Kopp-Neumann rule with large uncertainty.

Specific Heat of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
293-1144	10941	M.P. = 1083-1908 K.
273-1144	16736	
293-1144	20360	
488-922	31540	
10-1160	34753	Review article; M.P. = 1810 K.
	43639	M.P. = 1866 K.

4. Hadfield Manganese Steel

No experimental data are available for this particular steel. The temperature ranges of the available data for steels of similar composition together with the data source references are given in the following table.

Specific Heat of Manganese Steels

Temperature Range (K)	Reference	Remarks
373-773	9369	Fe + 13.5 Mn + 1.12 C.
37-1273	38083	Fe + 11 Mn + 3.7 C + 3.5 Si.

5. Boron Fiber Aluminum Metal Matrix Composite

No data are available.

6. Boron Fiber Epoxy Composite

No data are available.

7. Graphite Fiber Aluminum Metal Matrix Composite

No data are available.

8. Graphite Fiber Epoxy Composite

No data are available.

9. Acrylic Resins

Limited data for a few types of acrylic resins are available. The temperature ranges and data source references are given in the following table. Information on the acrylic resin of the type polymethylmethacrylate (Lucite) is given in the next subsection on Lucite.

Specific Heat of Acrylic Resins

Temperature Range (K)	Reference	Remarks
80-300	48787	Co-polymers of methylmethacrylate and methacrylic acid.
298-463	44898	Co-polymers of methylmethacrylate and 0-100% methacrylic acid.
25-300	90025	Polymethacrylic acid.
50-200	66583	Polyethylmethacrylate, poly-n-butyl acrylate, and poly-n-butyl methacrylate.

10. Lucite

The temperature ranges of the available data together with the data source references are given in the following table. Data recommendation will be possible up to the glass transition temperature.

Specific Heat of Lucite

Temperature Range (K)	Reference	Remarks
123-373	19987	PMMA.
10-260	24580	PMMA.
10-300	28387	PMMA.
87-273	29419	Plexiglass.

Specific Heat of Lucite (continued)

Temperature Range (K)	Reference	Remarks
123-473	37180	
250-450	39674	
16-260	33768	PMMA.
50-210	43278	PMMA.
298	58456	Plexiglass.
	52896	Plexiglass; T_{glass} = 388 K, T_{decomp} = 648 K.
313-453	64615	PMMA.
0-450	68936	PMMA.
20-300	53679	PMMA.

11. Polycarbonate Plastics

The temperature ranges of the available data for Lexan polycarbonate together with the data source references are given in the following table. Recommended values can be given for the entire temperature range.

Specific Heat of Polycarbonate Plastics

Temperature Range (K)	Reference	Remarks
110-310	28325	Lexan polycarbonate formed by condensation of phosgene and 4,4'-dihydroxyphenyl 2,2-propane.
110-550	36001	Lexan (G.E. Co.) polycarbonate; glass transition temperature Tg = 415 K; M.P. = 500-530 K.
293-473	37184	
330-500	41195	Transition near 420-430 K.
200-310	41551	
400	42497	
410-415	68988	

12. Silicone Resins

The temperature ranges of the available data together with the data source references for various silicone resins are given in the following table. Recommendations are possible only for silicone resins of the type listed in the table.

Specific Heat of Silicone Resins

Temperature Range (K)	Reference	Remarks
250-950	34753	Silicone rubber; chem seal 3802.
260-670	36145	Silicone resin casting, Dow Corning DC 2106.
370-670	36285	Silicone resin and silicone resin impregnated honeycomb; reaction at 470 K.
310-420	37387	Various silicone rubbers; reports also heats of combustion.
120-230	37897	Phenyl silane and dimethyl silicone, M. P. =233 K.
130-293	69782	Polydimethyl siloxene of SKTV type.
423-523	69783	Polydimethyl siloxene of SKT type, M. P. =230 K.
123-473	19987	Silicone rubber; phase transition near 230 K.
81-677	35530	Filled silicone rubber; two types.
220-700	37499	Phenyl silane resin casting.

13. Aluminum Oxide (Wesgo Al-300)

There are numerous papers on various types of Al_2O_3 of different purity. However, none is on Wesgo Al-300, which essentially is a sintered $Al_2O_3 + 1.4\ SiO_2 + 1.0\ CaO$. The data available for the similar type of alumina together with the data for the pure alumina and fused alumina can be used to estimate the C_p values for Wesgo Al-300 for the entire temperature range.

The temperature ranges of the available data together with the data source references are given in the following table.

Specific Heat of Aluminum Oxide

Temperature Range (K)	Reference	Remarks
298-973	59035	Wesgo Al-995.
300-1000	53797	Lucalox (G. E.).
5-2500	53339	Good review by TPRC staff.
200-1000	47943	A-14 grade Alcoa 95 Al_2O_3 sample.
	43731	99 Al_2O_3; M. P. = 2288 K.
1281-1469	39085	99.5 pure, McDanel refractory.
673-1173	35439	99.5 sintered Al_2O_3.
673-1173	69116	Alumina TA-600 (patented by Romania).

Specific Heat of Aluminum Oxide (continued)

Temperature Range (K)	Reference	Remarks
298	6524	99.5 sintered Al_2O_3, (87-93) Al_2O_3, 85 Al_2O_3.
0-3500	90028	JANAF review; crystal and fused; M. P. = 2315 K.
5-2300	61236	TPRC review.

14. Boron Nitride

The temperature ranges of the available data together with the data source references are given in the following table. These data can be used to generate recommended values over the entire temperature range.

Specific Heat of Boron Nitride

Temperature Range (K)	Reference	Remarks
0-3500	90028	JANAF review; T_{decomp} = 2600 ± 100 K (1 atmosphere).
19-2500	61236	TPRC review.
300-100	72303	95-97% β-variety.
530-2477	26008	$T_{subl.}$ = 3273 K.
310-2250	51482	98.5 pure; three varieties; $T_{subl.}$ = 3270 K.
298-1350	45833	USBM review, $T_{subl.}$ = 3273 K.
273-1313	56608	
400-1100	66891	

15. Calcium Aluminum Silicate (Corning 9753)

No data are available.

16. Magnesium Fluoride (Kodak IRTRAN 1)

The temperature ranges of the available data together with the data source references are given in the following table. These data are sufficient for generating recommended values.

AD-A128 906 THERMOPHYSICAL PROPERTIES OF AIRCRAFT STRUCTURAL MATERIALS IN SOLID AND M..(U) THERMOPHYSICAL AND ELECTRONIC PROPERTIES INFORMATION ANALYSIS.. 2/2

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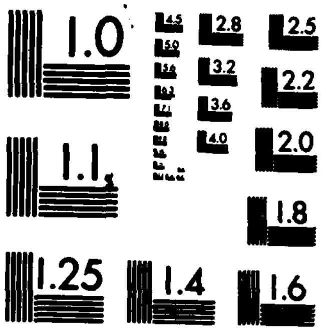
1.0
4.5
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6.3
7.1
8.0
9.0
2.8
3.2
3.6
4.0
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2.2
2.0
1.1
1.8
1.25
1.4
1.6

Specific Heat of Magnesium Fluoride (Kodak IRTRAN 1)

Temperature Range (K)	Reference	Remarks
	39947	IRTRAN 1, M.P. = 1528 K.
298	17017	IRTRAN 1.
	10380	Hot pressed.
298,727	25656	Compact sample; M.P. = 1528 K.
370-1789	1893	
300-1760	17036	M.P. =1536 K.
298-6000	19460	Review; M.P. =1536 K.
0-2500	90028	JANAF review; M.P. = 1536 K.
54-800	61236	TPRC review.

17. Pyroceram (Corning 9606)

Only one article listed below covers a wide temperature range.

Specific Heat of Pyroceram (Corning 9606)

Temperature Range (K)	Reference	Remarks
273-1273	25075	Softening temperature = 1623 K.

18. Silica (Fused)

The temperature ranges of the available data together with the data source references are given in the following table. These data can be used to recommend C_p values for the entire temperature range.

Specific Heat of Silica (Fused)

Temperature Range (K)	Reference	Remarks
50-300	34294	Vitreous silica.
	34753	Review article; M.P. = 1944 K.
298-973	37080	Silica glass; ceramic and quartz glass.
360-1420	47248	Fused silica; compilation.
320-930	6314	Fused quartz.
73-1073	6565	Fused silica.
0-4500	90028	Compilation; liquid silica; M.P. = 1996 K.
5-1520	61236	TPRC review; silica glass.
298-1200	1342	NBS review; silica glass.

19. Silicon

There are many articles and reviews which report C_p values covering the entire temperature range. The two reviews listed in the following table with other articles can be used as the basis for the recommendation of C_p values.

Specific Heat of Silicon

Temperature Range (K)	Reference	Remarks
1-3600	90027	Compilation; M. P. = 1685 K.
0-2500	90028	Compilation.

20. Silicon Carbide

The temperature ranges of the available data together with the data source references are given in the following table. These data will enable us to recommend C_p values from room temperature to the decomposition temperature. The decomposition temperature determined by the earlier works is about 500-1000 degrees lower than the currently accepted value of 3260 K.

Specific Heat of Silicon Carbide

Temperature Range (K)	Reference	Remarks
500-2900	63728, 65304	Measurements on three different samples.
390-2000	29311	USBM reports.
0-4000	90028	JANAF review.
300-1073	29054	Review article.
50-300	28368	
0-900	29021	
400-1273	21398	
473-1673	20600	
1273-3073	6972	

21. Silicon Nitride

The temperature ranges of the available data together with the data source references are given in the following table. These data cover the entire range from room temperature to the decomposition temperature.

Specific Heat of Silicon Nitride

Temperature Range (K)	Reference	Remarks
298-2000	14261	C_p values from ΔH_f and ΔG_f.
293	52882	
	29054	$T_{dissoc.}$ = 2173 K.
	26008	$T_{dissoc.}$ = 2200 K.
298-900	1342	NBS review.
273-850	13832	
0-3000	90028	JANAF review, $T_{dissoc.}$ = 2151 K at one atmosphere.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for Specific Heat*

Material	Normal Temperature	Normal Temp. to 50° below M.P.	50° below M.P. to M.P.	M.P. to 20° above
1. Al Alloy 2024	D	D	D	V⁻, M
2. Al Alloy 7075	D	D	D⁻	V⁻, M
3. Ti Alloy 6Al-4V	D	V⁻	V⁻, M	V⁻, M
4. Hadfield Manganese Steel	V	V⁻	M	M
5. Boron fiber aluminum metal matrix composite	M	M	M	M
6. Boron fiber epoxy composite	M	M	M	M
7. Graphite fiber aluminum metal matrix composite	M	M	M	M
8. Graphite fiber epoxy composite	M	M	M	M
9. Acrylic resins**	D	D	D	D⁻
10. Lucite**	D	D	D	D⁻, M
11. Polycarbonate plastics**	D	D	D	D
12. Silicone resins**	D	D	D	D
13. Aluminum oxide (Wesgo Al-300)	V	V	V	V
14. Boron nitride	D	D	V	V
15. Calcium aluminum silicate (Corning 9753)	M	M	M	M
16. Magnesium fluoride (Kodak IRTRAN 1)	D	V	V	V
17. Pyroceram (Corning 9606)	D	V⁻	M	M
18. Silica (fused)	D	D	D⁻	D⁻
19. Silicon	D	D	D	D
20. Silicon carbide	D	D	V	V
21. Silicon nitride	D	D	V	V

* See the explanation of codes on page 4.
** The available data are for some specific materials only.

I. Heat of Fusion

1. Aluminum Alloy 2024

No data are available from the literature. Estimated values may possibly be derived from the values of the constituent elements using empirical relation and/or the Kopp-Neumann rule.

2. Aluminum Alloy 7075

No data are available from the literature. Estimated values may possibly be derived from the values of the constituents elements using empirical relation and/or the Kopp-Neumann rule.

3. Titanium Alloy 6Al-4V

No data are available from the literature. Estimated values may possibly be derived from the values of the constituent elements using empirical relation and/or Kopp-Neumann rule.

4. Hadfield Manganese Steel

No data are available from the literature.

5. Boron Fiber Aluminum Metal Matrix Composite

No data are available from the literature.

6. Boron Fiber Epoxy Composite

No data are available from the literature.

7. Graphite Fiber Aluminum Metal Matrix Composite

No data are available from the literature.

8. Graphite Fiber Epoxy Composite

No data are available from the literature.

9. Acrylic Resins

For a number of acrylic resins the heat of fusion and fusion temperature are available, which, together with the data source references are given in the following table. Data recommendations are possible for those resins listed.

Heat of Fusion of Acrylic Resins

Fusion Temp. (K)	Heat of Fusion (cal g^{-1})	Reference	Material
295.2	9.4	90021	Atactic poly(n-hexadecyl methacrylate), PMA-16.
299.2	11.4	90021	Isotactic poly(n-hexadecyl methacrylate), PMA-16.
311.2	19.9	90021	Atactic poly(n-hexadecyl acrylate), PA-16.
309.7	18.8	90021	Isotactic poly(n-hexadecyl acrylate), PA-16.
319.2	24.3	90021	Atactic poly(n-heptadecyl acrylate), PA-17.
322.2	24.6	90021	Atactic poly(n-octadecyl acrylate), PA-18.
285.0	8.75	90022	Poly(dodecyl acrylates).
305.0	14.88	90022	Poly(tetradecyl acrylates).
298.9		90022	Poly(tetradecyl acrylates).
316.0	18.19	90022	Poly(hexadecyl acrylates).
311.3		90022	Poly(hexadecyl acrylate).
329.0	21.34	90022	Poly(octadecyl acrylate).
323.9		90022	Poly(octadecyl acrylate).
345.0	27.50	90022	Poly(docosyl acrylate).
339.5		90022	Poly(docosyl acrylate).
345.0	25.79	90022	Poly(docosyl acrylate).
265.0	0.95	90022	Poly(dodecyl alkylacrylamides).
291.0	5.43	90022	Poly(tetradecyl alkylacrylamides).
310.0	11.26	90022	Poly(hexadecyl alkylacrylamides).
318.0	7.70	90022	Poly(hexadecyl alkylacrylamides).
321.0	12.96	90022	Poly(octadecyl alkylacrylamides).
341.0	11.96	90022	Poly(octadecyl alkylacrylamides).
341.0	21.15	90022	Poly(docosyl alkylacrylamides).
289.0	5.78	90022	Poly(undecyl alkylacrylamides).
301.5		90022	Poly(undecyl alkylacrylamides).
319.0	17.37	90022	Poly(pentadecyl alkylacrylamides).
316.1		90022	Poly(pentadecyl alkylacrylamides).

Heat of Fusion of Acrylic Resins (continued)

Fusion Temp. (K)	Heat of Fusion (cal g^{-1})	Reference	Material
331.0	19.82	90022	Poly(heptadecyl alkylacrylamides).
327.6		90022	

10. Lucite

No data are available from the literature; however, Dupont literature on the various types of Lucite reveals that deflection temperature varies from 350-373 K under load of 18.5 Kg cm^{-2}.

11. Polycarbonate Plastics

The heat of fusion and the temperature of fusion are available and are given in the following table with the data source references.

Heat of Fusion of Polycarbonate Plastics

Fusion Temp. (K)	Heat of Fusion (cal g^{-1})	Reference	Material
506	33	90023	Lexan polycarbonate.
500-530	32	36001	Lexan polycarbonate.
	26	90025	Polycarbonate of bisphenol-A crystal.

12. Silicone Resins

The heat of fusion and the temperature of fusion are available and are given in the following table with the data source references.

Heat of Fusion of Silicone Resins

Fusion Temp. (K)	Heat of Fusion (cal g^{-1})	Reference	Material
230	5.7	69782	Polydimethyl Siloxene (PDMS) of SKTV type.
233	6.5	69783	Industrial grade Polydimethyl Siloxene of SKT type.

13. Aluminum Oxide (Wesgo Al-300)

There are several papers on various types of Al_2O_3, but none is on Wesgo Al-300. In a review of article [90028] heat of fusion is reported as 28.30 kcal $mole^{-1}$. From this and from the data published in other articles, the value for Wesgo Al-300 can be estimated.

14. Boron Nitride

The available data together with the data source references are given in the following table.

Heat and Temperature of Dissociation of Boron Nitride

Temperature of Dissociation (K)	Reference	Remarks
2600 ±100	90028	Dissociation under a total pressure of one atmosphere; $\Delta H_{f298} = -59.97 \pm 0.37$ kcal mole^{-1}.
3273	52252	Under N_2 pressure.
3270	26008	Under N_2 pressure.

15. Calcium Aluminum Silicate (Corning 9753)

No data are available.

16. Magnesium Fluoride (Kodak IRTRAN 1)

There are several articles which report heat of fusion of MgF_2 but none is on Irtran 1. The information given in the following table will serve as the basis for estimating the value for Irtran 1.

Heat of Fusion of Magnesium Fluoride

Heat of Fusion (kcal mole^{-1})	Reference	Remarks
13.98 (±0.1)	17036	Review article.
13.9	1893	

17. Pyroceram (Corning 9606)

This material softens at 1623 K. No data on the heat of fusion are available.

18. Silica (Fused)

A review article [90028] gives the heat of fusion at 1996 K as 2.29 kcal mole^{-1} which will serve as the basis for recommending the value.

19. Silicon

The results given in the following table are sufficient for recommending the value.

Temperature of Melting (K)	Reference	Remarks
1685	90027	Review article; ΔH_m = 12.082 kcal mole^{-1}.
1685 ± 3	90028	Review article; ΔH_m = 12.0 ± 0.1 kcal mole^{-1}.

20. Silicon Carbide

The review article listed in the table covers data published through 1967 for both α- and β-variety.

Temperature of Dissociation (K)	Reference	Remarks
3245	90028	α-variety; the "standard" heat of formation = -17.1 ± 1.5 kcal mole^{-1}.
3259	90028	β-variety; the "standard" heat of formation = -17.5 ± 1.5 kcal mole^{-1}.

21. Silicon Nitride

The available data together with the data source references are given in the following table.

Temperature of Dissociation (K)	Reference	Remarks
2173	29054	The standard heats of formation = -179.5 kcal mole^{-1}.
2200	26008	Sublimation.
2151	90028	The standard heats of formation = 178 ± 7 kcal mole^{-1}; review article.

22. Summary of Results of Feasibility Study of Data Estimation and Measurement

Results of the feasibility study of data estimation, based upon the available data and information presented in the preceding subsections and the analytical techniques for data estimation and prediction known to TEPIAC staff, are summarized in the table on the next page. This table contains also the results of the feasibility study of experimental determination based upon the existing measurement techniques and facilities.

Availability of Experimental Data and Feasibility of Data Estimation and Measurement for the Heat of Fusion*

		Heat of Fusion
1.	Al Alloy 2024	V⁻, M
2.	Al Alloy 7075	V⁻, M
3.	Ti Alloy 6Al-4V	V⁻, M
4.	Hadfield Manganese Steel	M
5.	Boron fiber aluminum metal matrix composite	M
6.	Boron fiber epoxy composite	M
7.	Graphite fiber aluminum metal matrix composite	M
8.	Graphite fiber epoxy composite	M
9.	Acrylic resins**	D
10.	Lucite	M
11.	Polycarbonate plastics**	D
12.	Silicone resins**	D
13.	Aluminum oxide (Wesgo Al-300)	V
14.	Boron nitride‡	D
15.	Calcium aluminum silicate (Corning 9753)	M
16.	Magnesium fluoride (Kodak IRTRAN 1)	V
17.	Pyroceram (Corning 9606)	M
18.	Silica (fused)	D
19.	Silicon	D
20.	Silicon carbide‡	D
21.	Silicon nitride‡	D

* See the explanation of codes on page 4.
** The available data are for some specific materials only.
‡ The available data are for the heat of dissociation/decomposition.

III. POTENTIALLY AVAILABLE EXPERIMENTAL FACILITIES

The capabilities of major experimental facilities in the United States to measure the desired transport, radiative, and thermodynamic properties were surveyed. The facilities under the cognizance of the armed services such as NRL, AMMRAC, and AFML were not included in this survey as they are being handled separately by the organizations involved. Over thirty laboratories were contacted and about one-half replied in writing. The results of this survey are summarized in a separate report.

IV. TENTATIVE ESTIMATE OF COSTS

Based upon the requirements for data extraction, analysis, synthesis, and estimation and the requirements for experimental determinations using available techniques and facilities, the costs for accomplishing the goals of this research program have tentatively been estimated, and these are summarized in the table on the next page.

Tentative Estimate of Costs

Property	Data Extraction, Analysis, Synthesis, and Estimation[a]		Experimental Determination[b]	Total
	Man-Hour	Cost		
1. Thermal conductivity	2,800	$ 45,000	$ 235,000	$ 280,000
2. Thermal diffusivity	1,600	25,000	200,000	225,000
3. Emittance	2,200	35,000	200,000	235,000
4. Reflectance	2,200	35,000	245,000	280,000
5. Absorptance	3,100	50,000	c	50,000
6. Transmittance	2,000	35,000	90,000	125,000
7. Thermal expansion	1,200	20,000	80,000	100,000
8. Specific heat	1,200	20,000	235,000	255,000
9. Heat of fusion	600	10,000	d	10,000
Total	16,900	$275,000	$1,335,000[e]	$1,610,000[e]

[a] Including literature search, data extraction, evaluation, analysis, synthesis, and generation of recommended or estimated values.

[b] Including only the measurements using existing techniques and facilities.

[c] Values for absorptance are to be derived from measurements on the other three thermal radiative properties.

[d] Included in the measurements on the specific heat.

[e] Including an additional $50,000 estimated for management of sub-contract efforts.

APPENDIX

DESCRIPTION OF MATERIALS

1. Aluminum Alloy 2024

Aluminum alloy 2024 is a wrought alloy with copper as the principal alloying element. Its nominal composition is 4.4% Cu, 1.5% Mg, 0.6% Mn, and balance Al. The melting range of this alloy is 775 to 911 K. This alloy requires solution heat-treatment to obtain optimum properties. In the heat-treated condition, the mechanical properties of this alloy are similar to, and sometimes exceed, those of mild steel. In some instances artificial aging is employed to further increase its mechanical properties. Alloy 2024 is perhaps the best known and most widely used aircraft alloy. This alloy was designated previously as 24S alloy.

2. Aluminum Alloy 7075

Aluminum alloy 7075 is a wrought alloy with zinc as the principal alloy element, and has a nominal composition of 5.6% Zn, 2.5% Mg, 1.6% Cu, 0.30% Cr, and balance Al. The melting range of this alloy is 750 to 911 K. In the solution heat-treated condition, alloy 7075 is among the highest strength aluminum alloys available and is used in air-frame structures and for highly stressed parts of an aircraft. This alloy was designated previously as 75S alloy.

3. Titanium Alloy 6Al-4V

Titanium alloy 6Al-4V has a nominal composition of 6% Al, 4% V, and balance Ti. The melting range of this alloy is 1803 to 1908 K. Its density is 4.424 g cm^{-3}, which is 56% that of steel. It can be heat-treated to having an ultimate strength in excess of 170,000 psi, and has excellent fatigue properties and crack propagation characteristics.

This alloy has a high alpha lean beta composition. The six percent aluminum addition stabilizes the alpha phase, resulting in an increase in the $\alpha+\beta \rightarrow \beta$ transformation temperature. It also increases the elevated temperature strength level.

The four percent vanadium content increases the strength level by two mechanisms: first by substitutional solid solution hardening and secondly, and perhaps more importantly, by stabilizing the beta or elevated temperature phase, thereby making the β to α hardening reaction possible through heat treatment. The addition of vanadium improves hot workability by causing more of the ductile beta phase to be present at hot working temperatures.

This alloy has the following different designations:

Republic Steel Co., Titanium Metal Division: Ti-6Al-4V
Special Metal Division: RS-120A

Crucible Steel Co., Titanium Division: C-120AV

Harvey Aluminum Co., Titanium Division: HA-6510

Reactive Metal Products: MST-6Al-4V

Aeronautical Material Specifications: 4928A

Military designation: OS-10737

4. Hadfield Manganese Steel

Hadfield manganese steel is an extremely tough nonmagnetic austenitic alloy. It was named after its inventor Sir Robert Abbott Hadfield (1858-1940), an English metallurgist, who was knighted in 1908 for his discovery of this steel in 1883 and many other metallurgical discoveries and inventions. This steel has a nominal composition of 10-14% Mn, 1.0-1.4% C, 0.1-0.3% Si, 0.1 P, and balance Fe. The melting range of this steel is estimated to be about 1470 to 1480 K. This steel is characterized by high strength, high ductility, and excellent resistance to wear. In the form of castings or of rolled shapes, it serves many industrial requirements economically and has built up an enviable record as the outstanding material for resisting severe service that combines abrasion and heavy impact.

5. Boron Fiber Aluminum Metal Matrix Composite

In the area of metal matrix, aluminum alloy matrix materials are the only ones currently commercially available. 6061, 2024, and 713 braze alloys are the aluminum alloys most commonly used.

Boron fiber aluminum matrix composite is made in the form of sheet or tape. The sheets are made by diffusion bonding boron fibers between two sheets of aluminum, e.g. 2024 or 6061. The tape is made by plasma spraying the 713 braze alloys. The tape is then diffusion or braze bonded into any desired configuration.

Boron filaments are formed by the vapor deposition of boron on a fine tungsten wire substrate within a reactor. Exposure of the tungsten substrate to the high temperature boron trichloride reactor environment results in a filament consisting of a boron sheath on a tungsten boride core. Boron fibers have higher tensile strength and modulus of elasticity than the graphite fibers commonly used in composite materials. Their melting point is higher than that of aluminum alloys generally used in conjunction with them. The boron filaments are currently produced by two principal sources, Hamilton Standard and Avco.

Composites of 6061 or 2024 aluminum alloys are not recommended for continuous service above 590 K although intermittent service to 645 K is possible. The products are available commercially in a wide range of laminate thickness including monolayer sheets in finished form. Virtually all of the actual hardware items built to date have been fabricated using standard fiber volume fractions of fifty percent.

It might be noted that composites using Borsic filaments are also available commercially. These are boron filaments coated with silicon carbide in order to adapt boron filaments to high temperature usage in composite.

The advantage of the boron fiber aluminum matrix composites is that along with its light weight it has a higher temperature and heat resistance than do the epoxy resin composites. Their nominal service range is about 220 K to 590 K.

6. Boron Fiber Epoxy Composite

This composite material consists usually of continuous boron filaments surrounded by a matrix of epoxy resin. It is usually produced in tape form so it can be used in further fabrication of specialized materials.

The boron filaments, as currently produced, are formed by vapor deposition of boron on a fine tungsten wire substrate within a reactor. Exposure of the tungsten substrate to the high-temperature boron trichloride reactor environment results in a filament consisting of a boron sheath on a tungsten boride core. Other means of producing boron filaments are currently being investigated which would eliminate the tungsten substrate.

The organic matrix resins most commonly used with boron filaments are modified epoxy resins available as commercial formulations developed specifically for this purpose. Other organic resins used include polyamides and phenolics. However, the state of the art with these resins is less advanced than for the epoxy materials.

The normal service temperature range of the boron fiber epoxy composite is dependent on the type of epoxy resin being used as a matrix. This range is nominally 220 K, where the epoxy becomes very brittle, to 450 K. Epoxy resin decomposes around 590 K.

7. Graphite Fiber Aluminum Metal Matrix Composite

There are three types of graphite fibers currently in large-scale production. These filaments have varied tensile strengths, moduli of elasticity and densities.

Graphite fibers for use in composite materials are made by the carbonization of organic fibers. Polyacrylonitrile (PAN) is most commonly used today, but acrylic and rayon fibers have been used to some extent in the past. The mechanical properties of the fibers depend on the temperatures used in the carbonization process. Temperatures of 2800-3300 K yield fibers with high moduli of elasticity but with relatively low tensile strength while temperatures of 1800-2300 K result in fibers of the highest tensile strength but only moderate elasticity. The melting point of the graphite fibers is much higher than the aluminum matrix components generally used. The fibers are available in short lengths (about 48 inches) and continuous lengths up to 3000 feet. The mechanical properties of these two forms are somewhat different.

Aluminum alloys 2024 and 6061 are frequently used in composite materials. The maximum continuous service temperature for these alloys is generally considered to be about 590 K. The composite material is produced by press diffusion bonding under vacuum.

8. Graphite Fiber Epoxy Composite

Composite materials have received great interest in the last decade because they provide unusual combinations of properties which cannot be obtained with any single, homogeneous substance. In aircraft and missile design, they have provided structural materials of very high strength and elastic modulus which also have low densities.

The graphite fibers used in composites are made by the carbonization of organic filaments. The filaments most often used today are made from polyacrylonitrile (PAN) although rayon and acrylic fibers have been used to a limited extent. The mechanical properties of graphite fiber depend on the temperatures used in the carbonization process. Temperatures of 2800-3300 K result in fibers with high elastic modulus but relatively low tensile strength. Temperatures of 1800-2300 K yield fibers of the greatest tensile strength but only moderate modulus of elasticity. The density of the fibers varies from 1.74-1.94 g cm^{-3} depending on the carbonization temperatures used. The filaments are normally produced in untwisted, loose bundles, or tows, consisting of ten thousand fibers.

Modified epoxy resins developed specifically for use in composites with graphite fiber are available commercially. These are thermosetting resins used for low pressure laminating which normally cannot be used in continuous service above about 450 K although intermittent service at temperature up to 490 K is possible. Many of the various epoxy resins used as matrix constituents of composites are proprietary formulations whose exact chemical compositions are not available.

For aerospace design, graphite fiber-epoxy composites are generally supplied by the manufacturer as prepregs. These are tapes or broadgoods consisting of the graphite fibers impregnated with the epoxy resin matrix which have been only partially cured and consequently have a limited shelf life and require special storage facilities. The prepregs are used in the fabrication of laminates whose layer orientations are tailored to match individual design requirements. Consequently, large numbers of individually different crossplied laminates are likely to be encountered, each of which has distinctive properties and characteristics, and hence must be distinctly identified whenever it is to be associated with specific quantitative data.

9. Acrylic Resins

The four major categories of acrylic resins include polymethacrylate, polyacrylate, poly(methyl methacrylate), and copolymer of acrylonitrile. The list of esters range from methyl to lauryl, C_1-C_{15}. Because of the many combinations possible there are at least 40 varieties of acrylic resins commercially available. Lucite is a trade name of DuPont for poly(methyl methacrylate) which will be described in the next subsection. Other trade names for the various acrylic resins include Acryloid, Acrysol, Acryrin, Hycar PA, Acrilan, Creslan, Dynel, Orlon, Plexiglass, Vernonite, etc. These materials are manufactured in a wide range of colors and are in demand where aesthetic considerations predominate. They possess low specific gravity, low water absorption, good weather ability, and tensile strengths but only moderate heat resistance and low hardness. They soften from 250 to 400 K and are more easily scratched than glass.

According to the Reference [90004], the softening points of acrylics are as follows:

Acrylics	Softening Point (K)
Polymethylacrylate (PMA)	277
Polyethylacrylate (PEA)	248
Polymethylmethacrylate (PMMA)	397
Polyethylmethacrylate (PEMA)	339
Poly n-butyl methacrylate (PBMA)	303
Polyacrylonitrile	511

The polymerization of acrylate and methacrylate esters is carried out in water suspension with peroxide catalyst. The resulting polymer is washed, dried, and blended with plasticizers and colorants before pelletizing for use as molding powders.

$$CH_2=\overset{H}{\overset{|}{C}}-\overset{O}{\overset{\|}{C}}-OCH_3 \xrightarrow[\text{peroxide}\ H_2O]{80\text{-}100\ C} \left[-CH_2-\underset{COOCH_3}{\underset{|}{CH}}-\right]_n$$

poly(methylacrylate)

$$CH_2=\overset{CH_3}{\overset{|}{C}}-\overset{O}{\overset{\|}{C}}-OCH_3 \xrightarrow[\text{peroxide}\ H_2O]{80\text{-}100\ C} \left[-CH_2-\underset{COOCH_3}{\underset{|}{CCH_3}}-\right]_n$$

poly(methyl methacrylate)

10. Lucite

Lucite is a propriatory acrylic resin, poly(methyl methacrylate), manufactured by DuPont Co. Plexiglass is essentially the same material manufactured by Rohm and Haas.

It is a rigid clear, thermoplastic material having the best weathering properties of any transparent plastic. Industrial uses include optical applications such as TV screens and camera lenses. The softening temperature of Lucite is 397 K.

Lucite acrylic resins are available in a number of formulations tailored for specific applications.

The preparation of this material is consistent with the general scheme for preparation of acrylic resins.

$$CH_2=\overset{CH_3}{\overset{|}{C}}-\overset{O}{\overset{\|}{C}}-OCH_3 \xrightarrow[\text{peroxide}\ H_2O]{80\text{-}100\ C} \left[-CH_2-\underset{COOCH_3}{\underset{|}{CCH_3}}-\right]_n$$

poly(methyl methacrylate)
Lucite

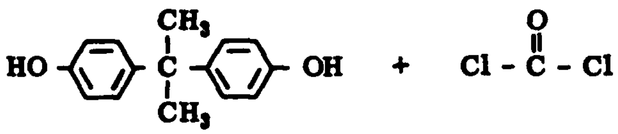
11. Polycarbonate Plastics

Polycarbonates are transparent thermoplastics, showing superior strength and high temperature resistance. They also possess excellent electrical resistance, moldability, and high dielectric strength. Their unique hardness properties allow polycarbonates to substitute for metals in some applications, as in plastic rivets and bolts.

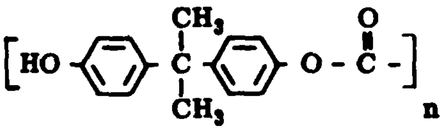
Trade names of polycarbonate are "Lexan" for General Electric and "Merlon" for Mobay. The softening point of Lexan is 428 K and that of Merlon is 410 K. The

heat distortion temperature and mold temperature are 406-411 K and 561-589 K, respectively.

Polycarbonates are formed by the condensation of polyphenols (usually Bisphenol-A), with phosgene.



Bisphenol-A (4,4'-isopropylidene diphenol) Phosgene



Polycarbonate

12. Silicone Resins

These polymers may be resins, rubbers, or liquids. They are characterized by resistance to heat, oxidation, and weathering; water repellency; near independence of physical properties with temperature; and resistance to electrical breakdown. Their thermal degradation temperature is about 473 to 873 K.

Industrial uses include silicone release agents, lubricants, adhesives, laminating resins, electrical insulation, molding compounds, and additives. Trade names include Silastic, Polysil, Versilube, Dow Corning Silicone, etc.

In the United States, major companies producing silicones for industrial use include Dow Corning Corporation, General Electric Company, and Union Carbide Corporation.

For the purpose of aircraft design, the application of silicone resins may be classified in the following three ways:

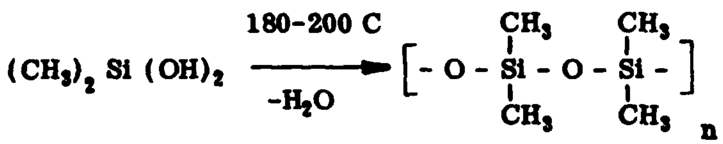
(1) Silicone laminating resins - These are used primarily in bonding glass cloth to produce structural and electrical laminates. They are also used to bond asbestos paper and cloth. Silicone-glass laminates have excellent resistance to heat and heat aging.

(2) Interlayer for laminates glass - Silastic Type K Interlayer serves as the center layer in safety glass windshield for supersonic aircraft.

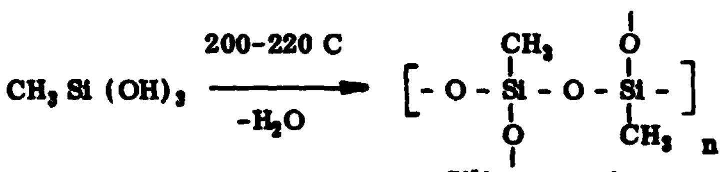
(3) Silicone molding compounds - These are thermosetting materials that can be formed by either compression or transfer molding techniques. For high-impact, glass fiber-filled silicone molding compounds, the heat distortion temperature is about 755 K. Parts molded from silicone molding compounds find use as both structural and dielectric materials in aircraft and missiles.

Several silicone resins have been considered for application in aerospace construction. Poly(dimethylsilanediol) with melting point 740 K has been considered for use as a matrix material for flexible windows and domes in manned spacecraft, although it has been suggested that it has insufficient tear resistance for this purpose. Polyphenyl silicone has been considered for use as a paint-like organic coating for spacecraft, designed to control emission and absorption of radiant energy. Silicone DC 808 has been considered for similar uses. Silicone XRG-2044 has been considered for use as a coating for solar cells. Owens Illinois "Glass Resin 100" has been studied for possible use as a lightweight optical material for aerospace reconnaissance. Some elastomers are used for oxygen hoses, space suit, and cabin seals. Silicone resins are also used as ablation shields for space ships.

Silicones consist of chains of alternate Si and O atoms. The chains are modified by various organic groups attached to Si, or by crosslinking. Silicone polymers are prepared by condensation of di- or trihydroxymethylsilanes.



Silicone rubber



Silicone resin

13. Alumimum Oxide (Wesgo Al-300)

The Wesgo Al-300 alumina is produced by Western Gold and Platinum Co., Belmont, California. It contains 97.6% aluminum oxide. Its density is 3.76 g cm^{-3}, about 95% of the theoretical value, though the manufacturer claims zero porosity. The hardness of the material is 75 (Rockwell 45 N). The maximum working temperature

is 1920 K. The melting point of pure alumina has been reported around 2315 to 2326 K.

There is another version of the material made by the same manufacturer, the Wesgo Al-300S alumina. This material has stronger flexural strength and compressive strength, and is harder than Al-300.

14. Boron Nitride

Boron nitride (BN, molecular weight 24.82) exists in two forms. One is like graphite in layers of hexagonal rings. The other, called Borazon and formed at high pressure (85,000 atm) and high temperature (2070 C), is a cubic or diamond crystal. In addition, boron nitride fibers 5 to 7 microns in diameter and 15 to 25 cm long are available for industrial usages.

Boron nitride is a refractory material. It does not melt, but sublimes at about 3270 K under nitrogen pressure. It has also been reported that boron nitride decomposes at about 2600 K in air at atmospheric pressure. It is practically insoluble in water. It does not conduct electricity. The crystal modification, Borozon, is harder than diamond, and is probably the hardest material on earth.

The application of boron nitride includes furnace insulation, high temperature lubrication (the graphite like form), dielectric, wave guide, heat shield for plasma, nose cone windows, etc.

15. Calcium Aluminum Silicate (Corning 9753)

Corning 9753 is a solid solution of 30% CaO, 40% Al_2O_3, and 30% SiO_2. It melts around 1723 to 1773 K.

16. Magnesium Fluoride (Kodak IRTRAN 1)

IRTRAN 1 is a hot pressed, sintered polycrystalline compact of magnesium fluoride (MgF_2) produced by Eastman Kodak Co. It appears translucent, in colors ranging from creamy beige to dark green. The infrared cut off for this material is 9 μm as compared to 7.5 μm for ordinary MgF_2. The physical and chemical properties are in general favorable for use as optical element. It does not exhibit cleavage, has high melting point (1528 K), and has high thermal shock resistance. It is used as windows, domes, prisms, and filter substrates for infrared systems.

17. Pyroceram (Corning 9606)

Pyroceram brand glass-ceramic Code 9606 is a microcrystalline material composed of silicon dioxide, aluminum oxide, magnesium oxide, and a small amount of titanium dioxide, and is produced by Corning Glass Works. The ingredients are melted together at temperatures of the order of 1900 K using special techniques to insure uniform composition, constant density, freedom from bubbles and striations, and uniform electrical properties. Pyroceram 9606 is non-porous and considerably harder than glass. It was specifically developed to give uniform electrical properties throughout the body at microwave frequencies at elevated temperatures for radome applications. Its softening temperature is about 1623 K.

18. Silica (Fused)

Fused silica is also known as silica glass, vitreous silica, and fused quartz. It has a molecular weight of 60.0%. Its density is about 2.2 g cm^{-3}. It melts at 1996 K and boils at about 2500 K. It is practically insoluble in water. One distinction in its property is that the coefficient of thermal expansion is among the lowest of all known materials.

The potential usefulness of fused silica as an infrared dome material for missiles has been studied. It was found that fused silica is excellent for use in the short wavelength range. However, it cannot be used in the 3 to 5 μm range, since such a dome suffers an appreciable transmission loss when temperature increases to 800 K from normal ambient temperature. Several manufacturers have produced commercial formulations of fused silica developed especially for use in the ultraviolet or infrared ranges.

19. Silicon

Silicon is a nonmetallic element which is steel-gray and has a metallic luster when crystalline, and a dark-brown mass when amorphous. Crystalline silicon has a diamond cubic structure with a density of 2.33 g cm^{-3} at 293 K. It melts at about 1685 K and boils at about 2753 K. Natural-occurring silicon is composed of three stable isotopes, the most abundant being ^{28}Si which constitutes 92.21%. Five other radioactive isotopes are known to exist. Silicon is the second most abundant element in the crust of the earth (28.15% by weight in the continental crust), being exceeded only by oxygen.

Silicon is a brittle material below 1273 K, but above this temperature it can be caused to undergo substantial plastic deformation. Silicon has been studied for use

as infrared dome material for small air to air missiles [10703]. For this purpose it can be used in the 1-12 μm range up to 523 K and over the 6-7 μm range to a temperature of 593 K. Above this temperature it becomes increasingly opaque. Extremely small amounts of impurities greatly curtail its transmittance. For dome construction, the most feasible fabrication method appears to be a form of shell casting [48097]. Vapor deposition techniques for making domes have also been studied [48097].

20. Silicon Carbide

Silicon carbide is an exceedingly hard, green to bluish-black, iridescent, sharp crystal with hardness of 9.5 (next hardest substance to diamond). It has been considered as a potential candidate for laser dome material.

Silicon carbide can be produced by heating cork and sand (and salt as flux) in an electric furnace. The product contains 29.97% carbon and 70.03% silicon with a density of 3.23 g cm^{-3}. Several other technological methods exist for producing silicon carbide. Materials obtained by different production scheme vary in chemical composition, porosity, structural mechanical features, phase composition, texture, etc.

Silicon carbide does not melt without decomposition, and it may sublime without complete dissociation within a limited range of temperatures. The decomposition or dissociation temperature depends somewhat on the atmosphere and on the composition of the material. The decomposition temperature has been reported as high as 3260 K and as low as 2500 K.

21. Silicon Nitride

Silicon nitride (Si_3N_4) is a hard refractory with a useful service temperature of about 1500 K. It dissociates at about 2200 K. It has been reported that there are two types of crystal structure of silicon nitride, α-Si_3N_4 and β-Si_3N_4, both of which are hexagonal but with different lattice constants in the c-axis [52257]. Four types of crystal structure of Si_3N_4 have also been reported [29667].

Silicon nitride is a good electrical insulator with reported resistivities of 10^{12} Ωcm at room temperature and 10^{6} Ω cm at 1300 K. It has a very low coefficient of thermal expansion; as a result, its thermal shock resistance is very good. Upon being heated in air, its oxidation product, SiO_2, coats its surface giving it good oxidation and chemical resistance. More recently, in integrated circuitry work, silicon wafers have been coated with an amorphous film which has been identified as silicon nitride.

Dense silicon nitride has been developed primarily for use in gas turbine at temperatures up to 1500 K. It is produced by hot pressing and sintering silicon powder compact in a nitrogen atmosphere at high pressure and at a temperature near the melting point of silicon (1685 K). Using this technique, laboratory preparations have resulted in samples of 98% purity.

FILME

7–8